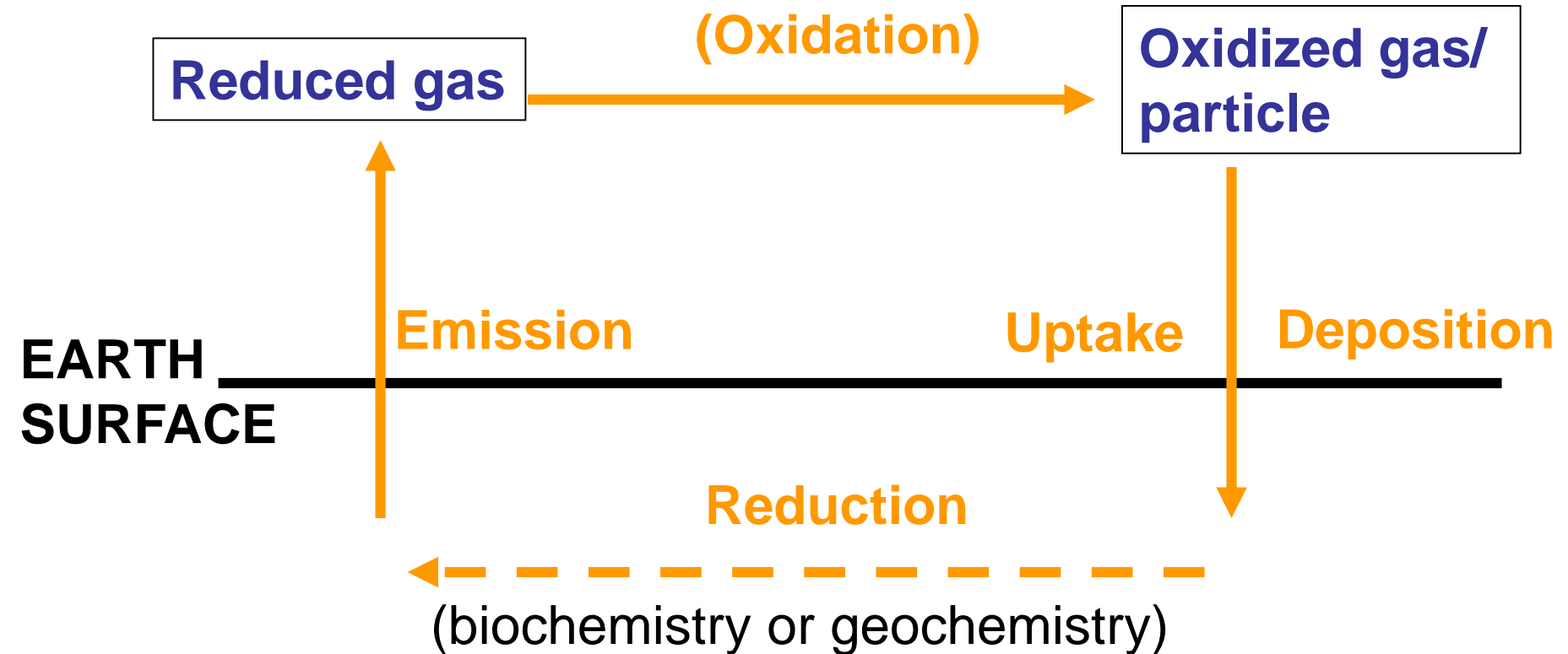


# This Week: Global Biogeochemical Cycles - Carbon

- **Short-term biosphere-driven cycles**
  - Terrestrial biosphere
  - Marine biosphere
- **Long-term inorganic cycles**
  - Weathering-volcanism thermostat

# Global Biogeochemical Cycles



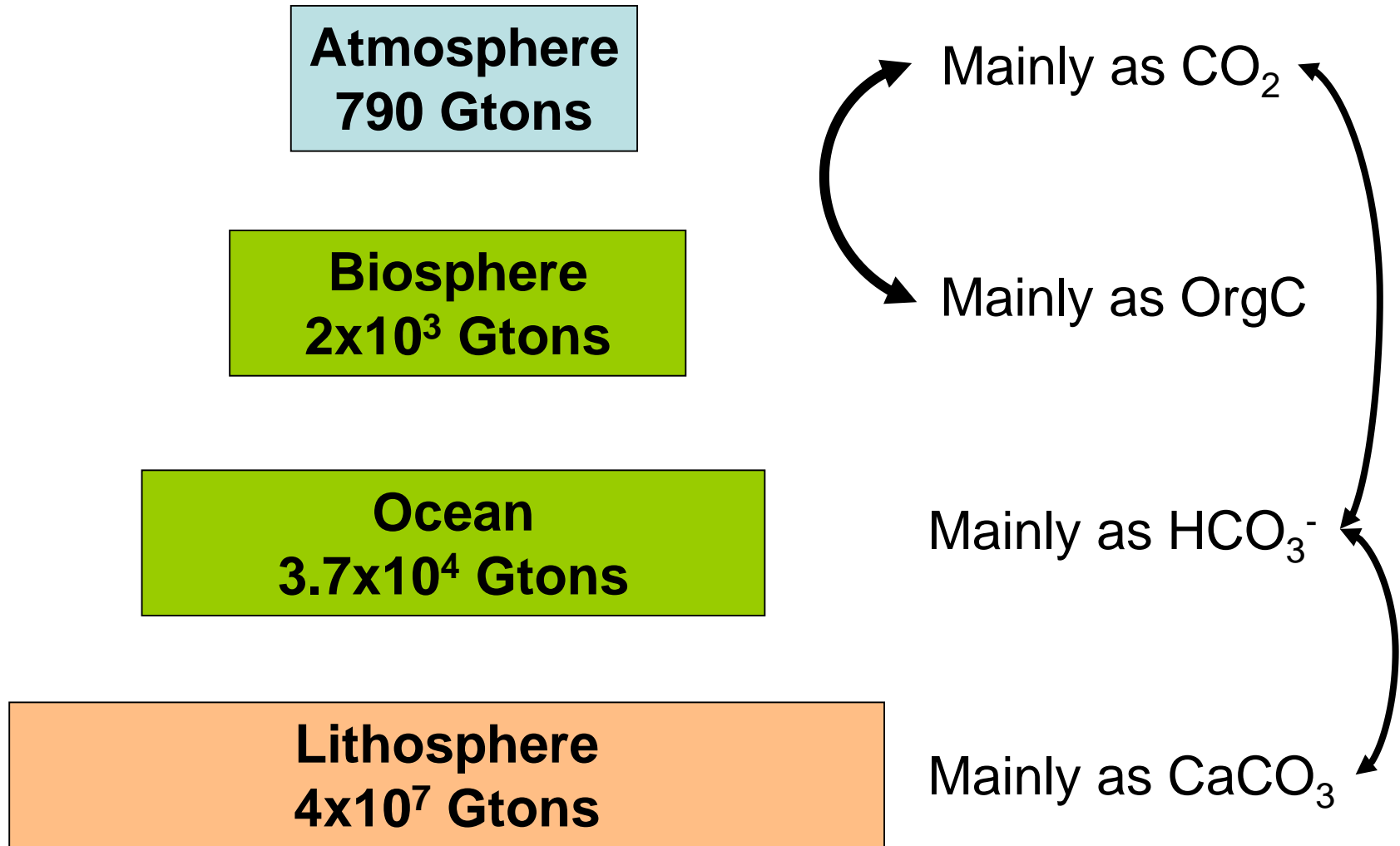
# Mass Units of Geologic Scale

- 1 Gigaton =  $1 \times 10^9$  tons =  $1 \times 10^{12}$  kg
- $1 \times 10^{12}$  kg =  $1 \times 10^{15}$  g = 1 Petagram

**→ 1 Gigaton = 1 Petagram**

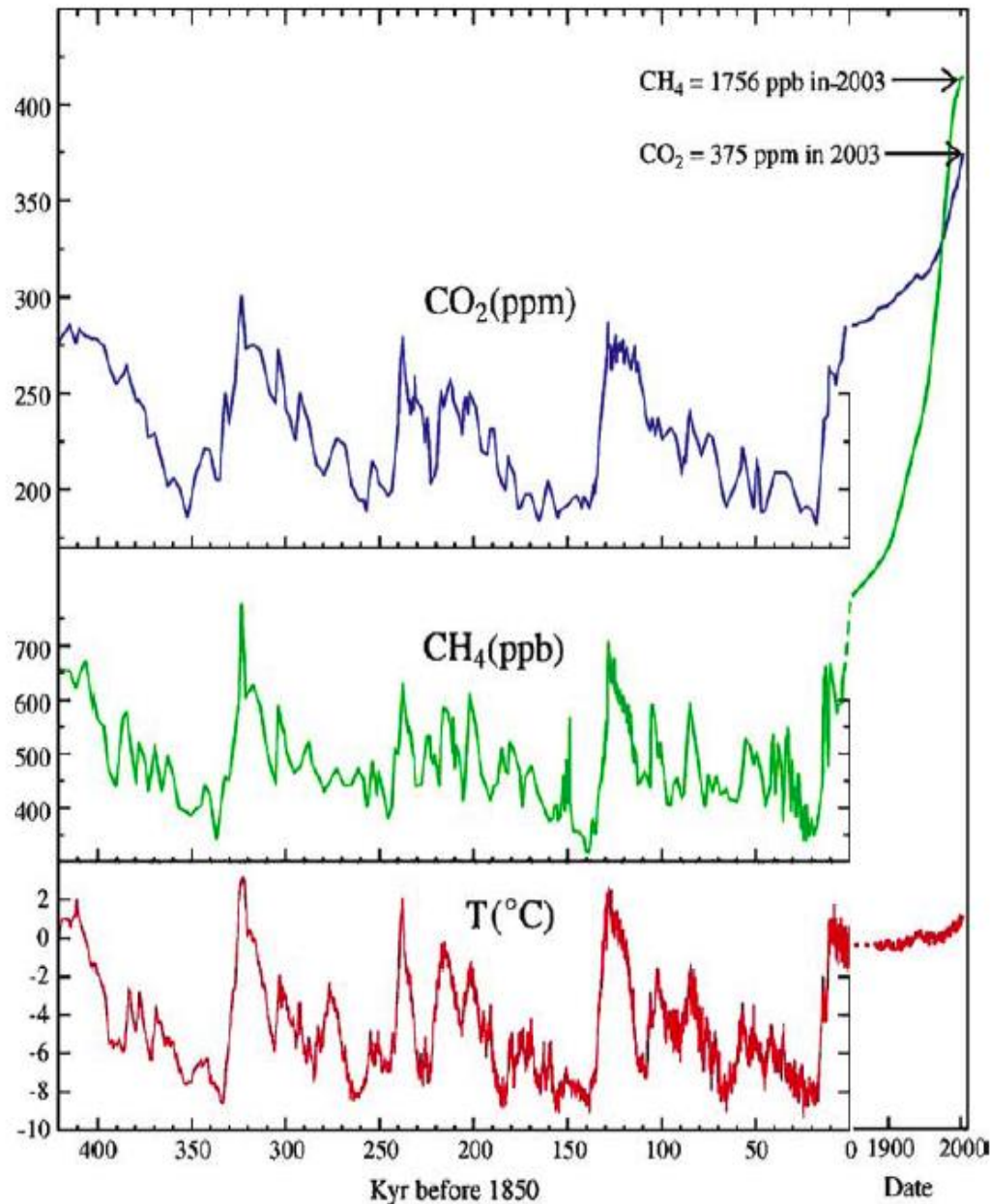
**→ 1 ppm of atm. CO<sub>2</sub> ~ 2 Gtons C**

# Reservoirs of Carbon



Carbon in the atmosphere and oceans mostly *inorganic*

# Slow Carbon Variations



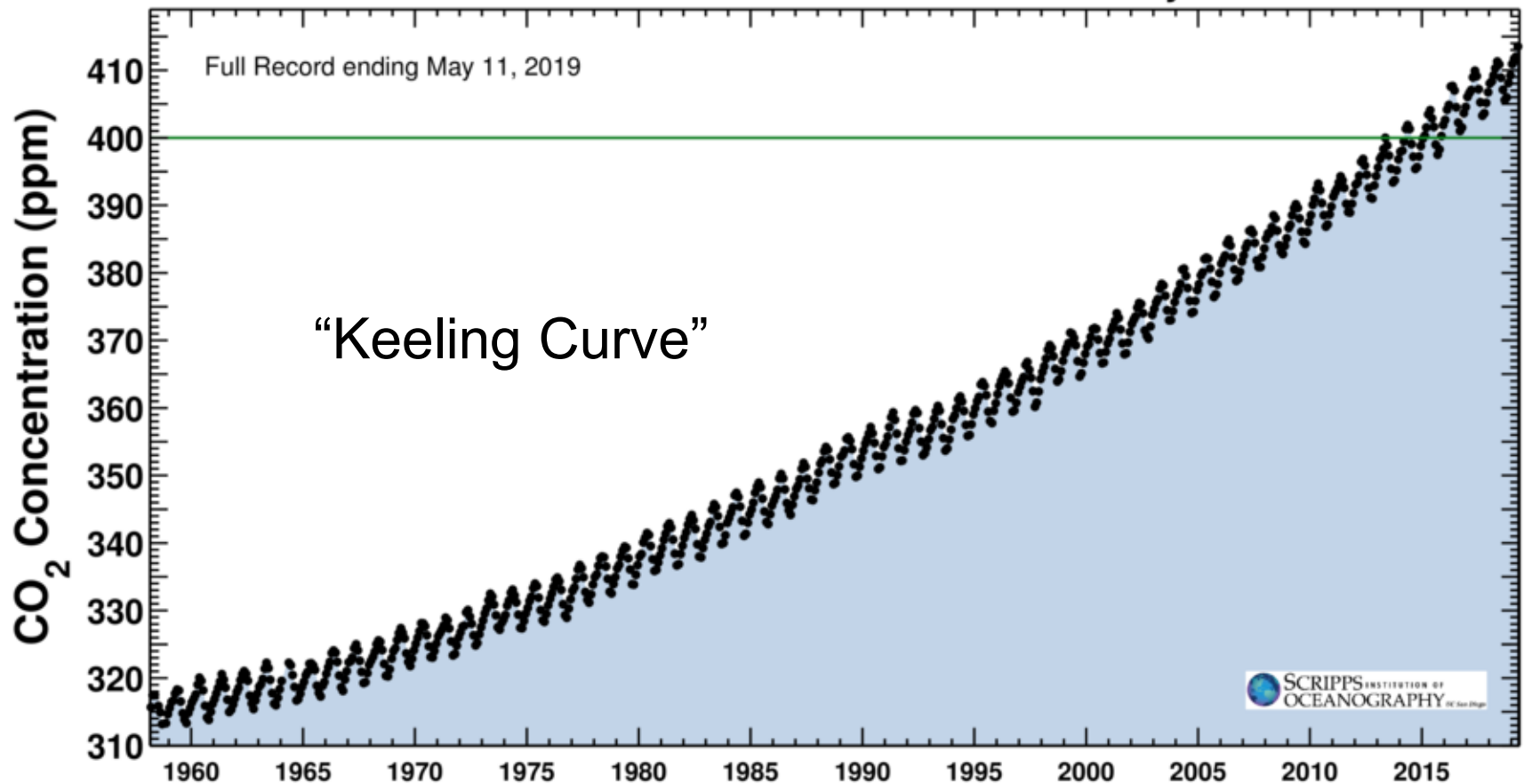
Large (but slow)  
natural changes

# Modern Era Atmospheric Carbon

Latest CO<sub>2</sub> reading  
May 11, 2019

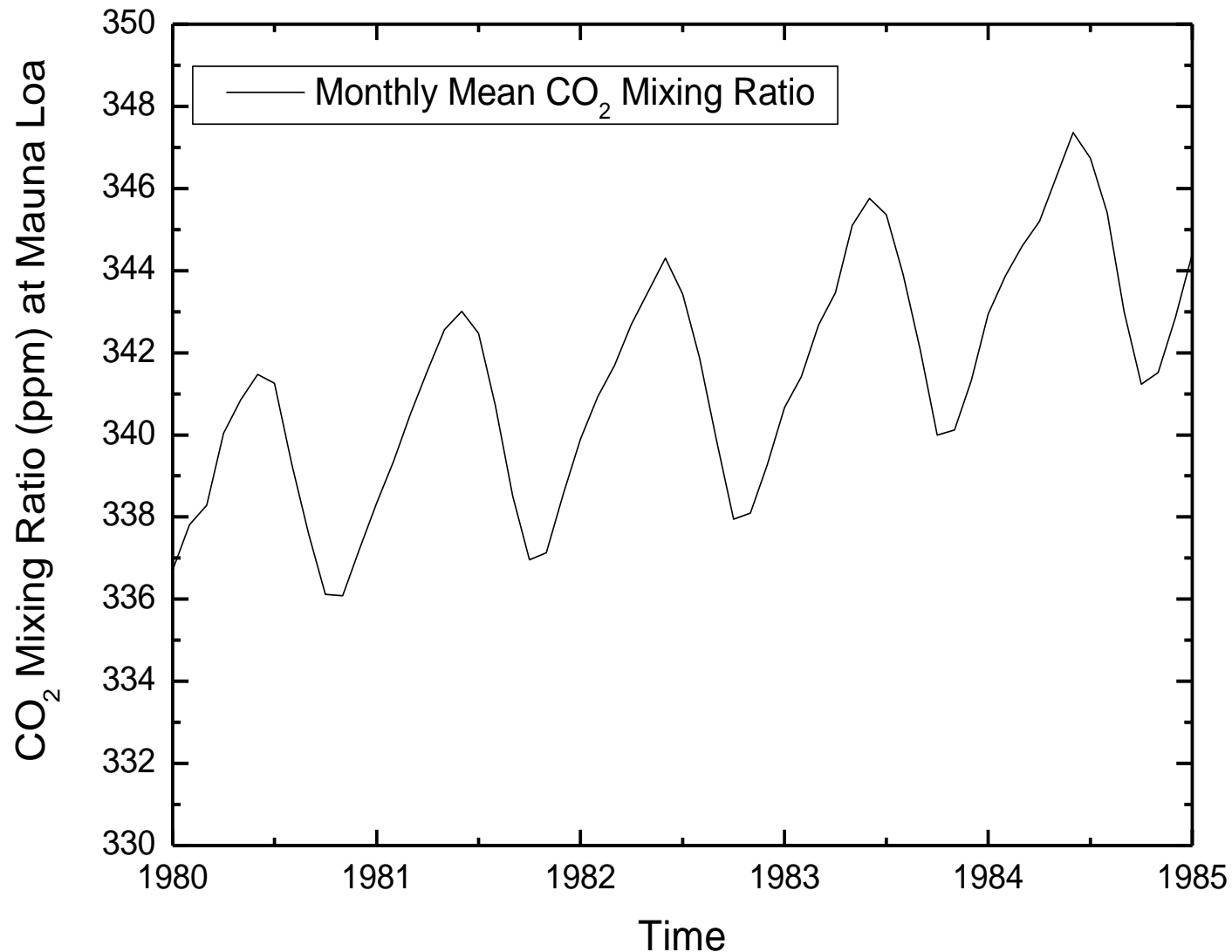
415.26 ppm

Carbon dioxide concentration at Mauna Loa Observatory



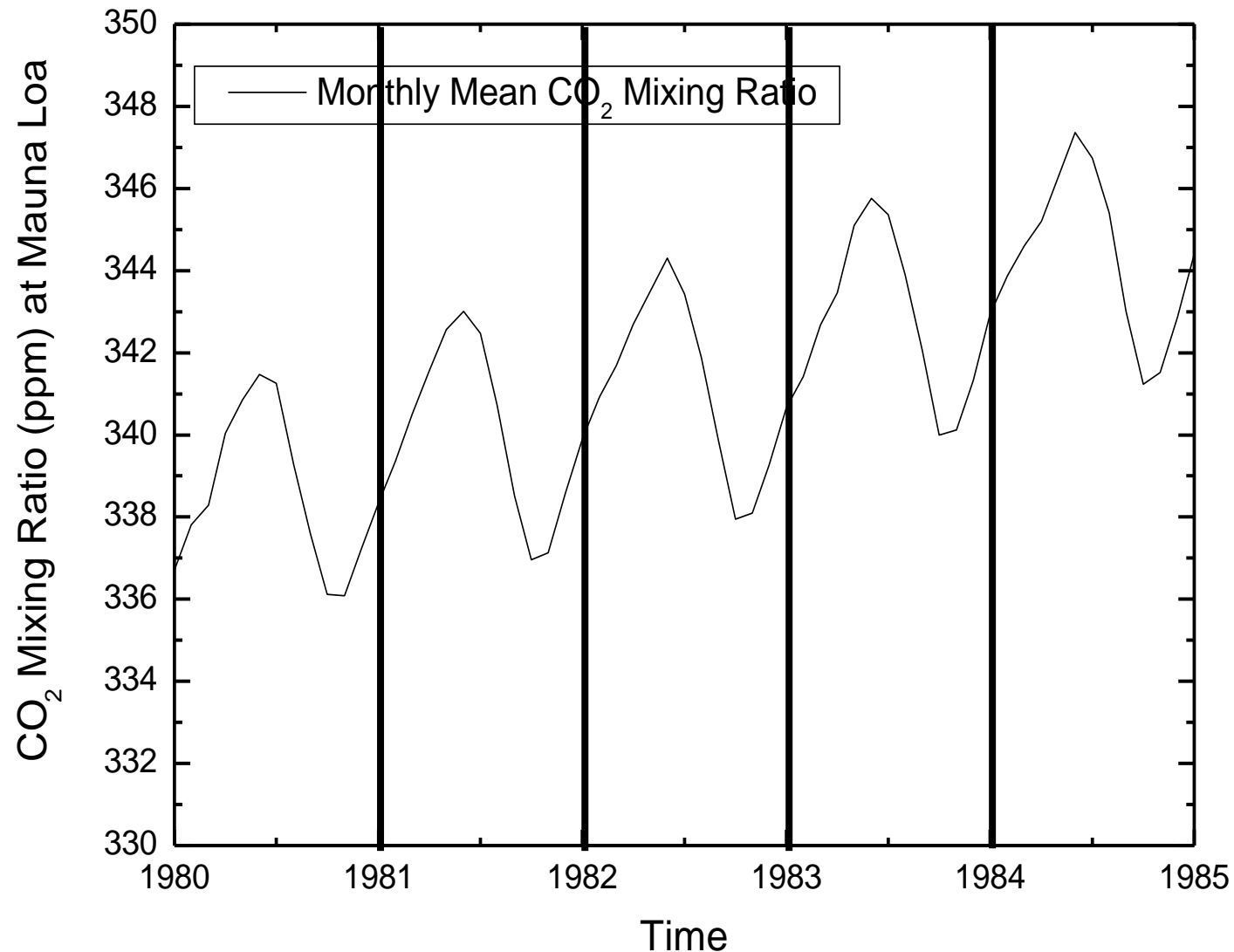
<https://scripps.ucsd.edu/programs/keelingcurve/>

# Fast Carbon Variations: CO<sub>2</sub> Seasonal Cycle



**Atmosphere responds to biosphere on short timescales 7**

# Fast Carbon Variations: CO<sub>2</sub> Seasonal Cycle



**Atmosphere responds to biosphere on short timescales 8**



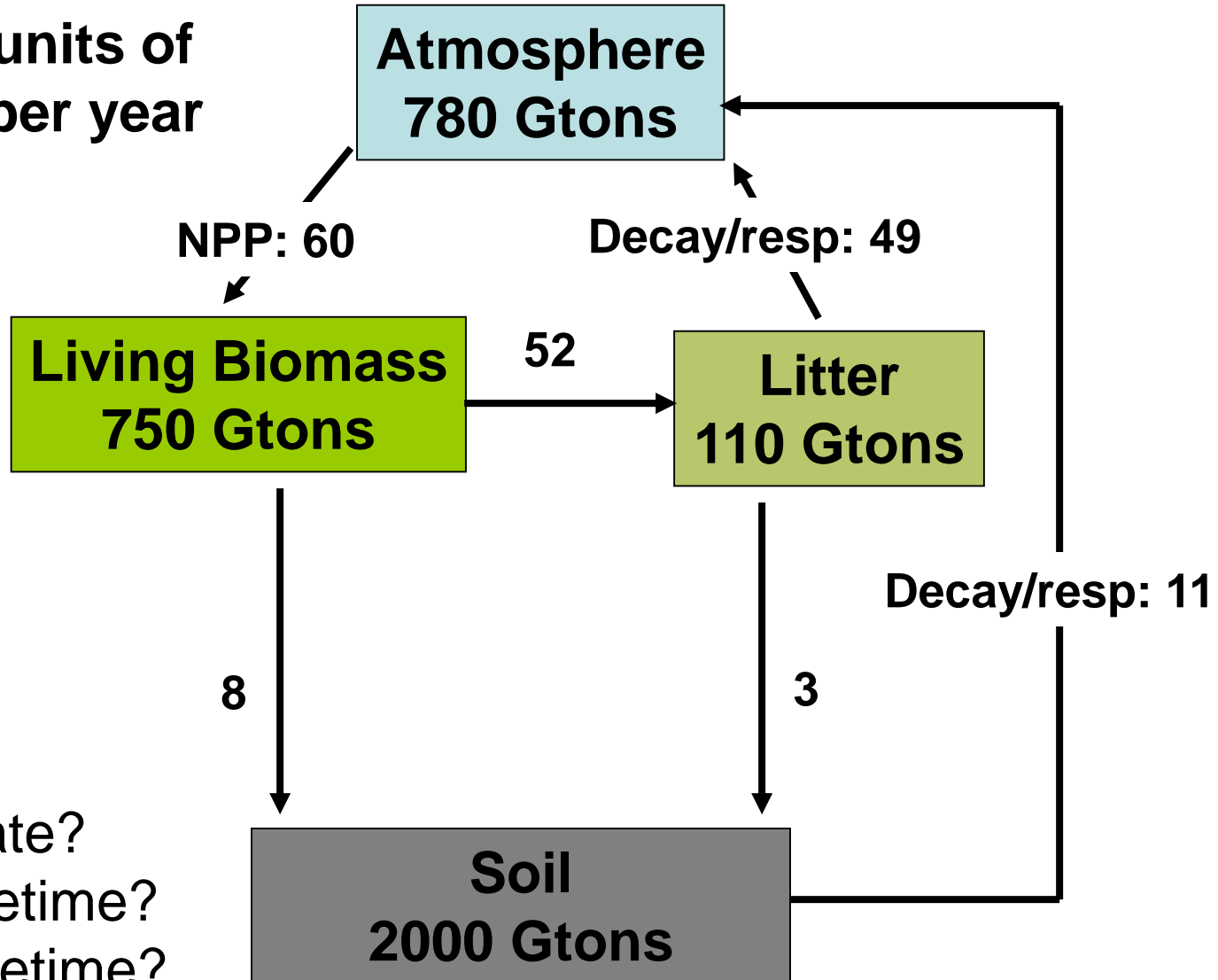
# Fast Flows of C: Organic Carbon Cycle

---



# Terrestrial Biosphere OrgC Cycle

Flows in units of  
Gtons C per year



Steady State?  
Longest lifetime?  
Shortest lifetime?






**W. Brazil (Whitaker/Reuters)**

# Poll Question

**W** Net deforestation causes atmospheric CO2 to

 When poll is active, respond at [Pollev.com/joelathornto254](https://Pollev.com/joelathornto254)

 Text **JOELATHORNT0254** to **22333** once to join

Increase

Decrease

Stay the same





Total Results: 0



# Poll Question

**W** Humans are part of the terrestrial biosphere. We eat OrgC and respire CO<sub>2</sub>. Population will increase in the future, thus, just by breathing we will increase atmospheric CO<sub>2</sub>.

 When poll is active, respond at [Pollev.com/joelathornto254](https://Pollev.com/joelathornto254)  
 Text **JOELATHORNT0254** to **22333** once to join

True

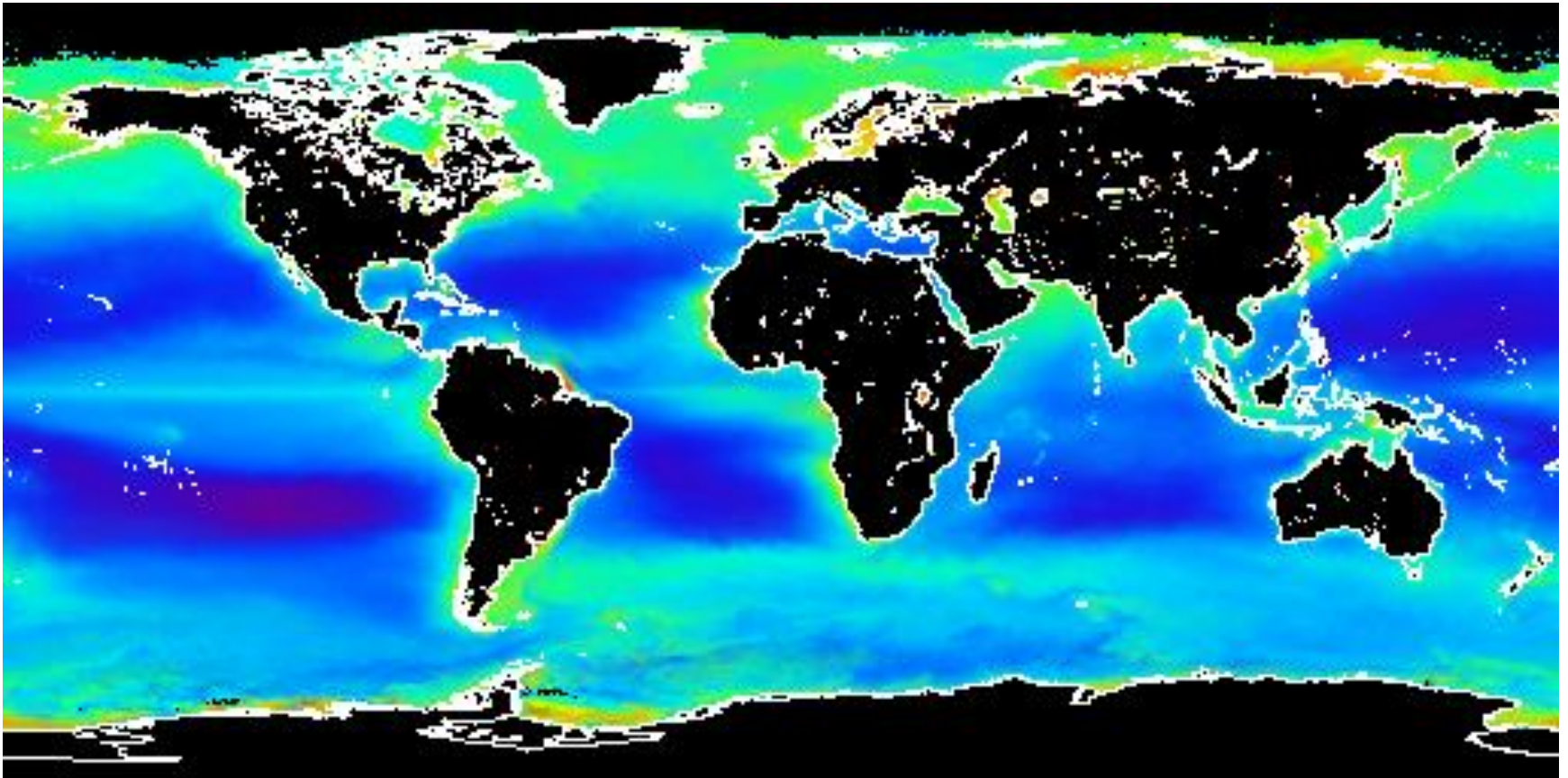
False

Total Results: 0

# Marine Productivity

Global map of ocean color from SEAWIFS satellite  
chlorophyll → phytoplankton (where the nutrients are)

remember upwelling and convection?

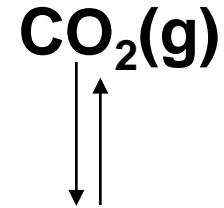


# Marine Biosphere Organic Carbon Cycle

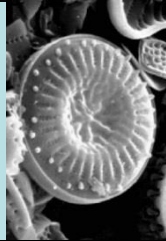
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# Marine Organic C Cycle



**Surface Ocean**



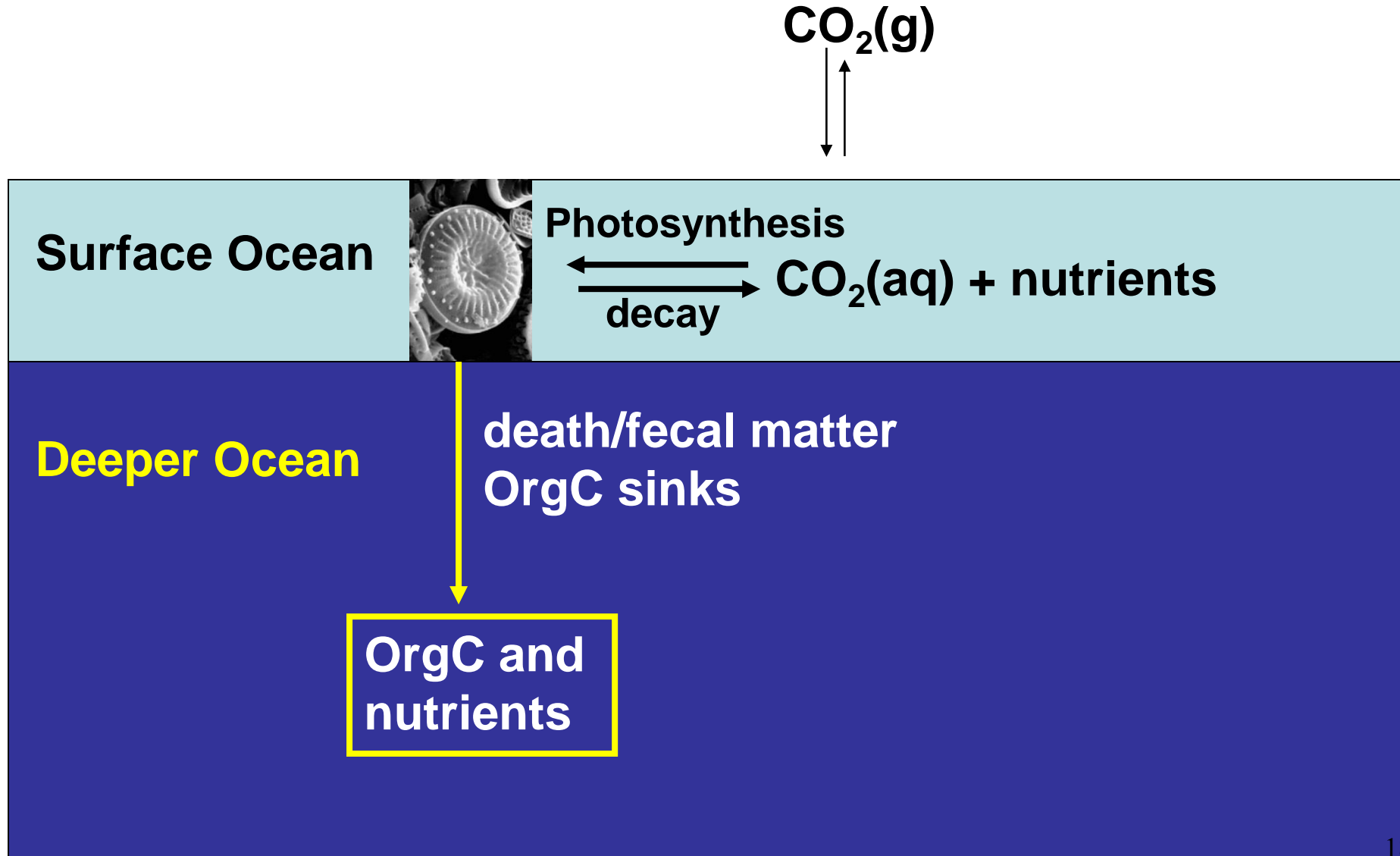
**Photosynthesis**



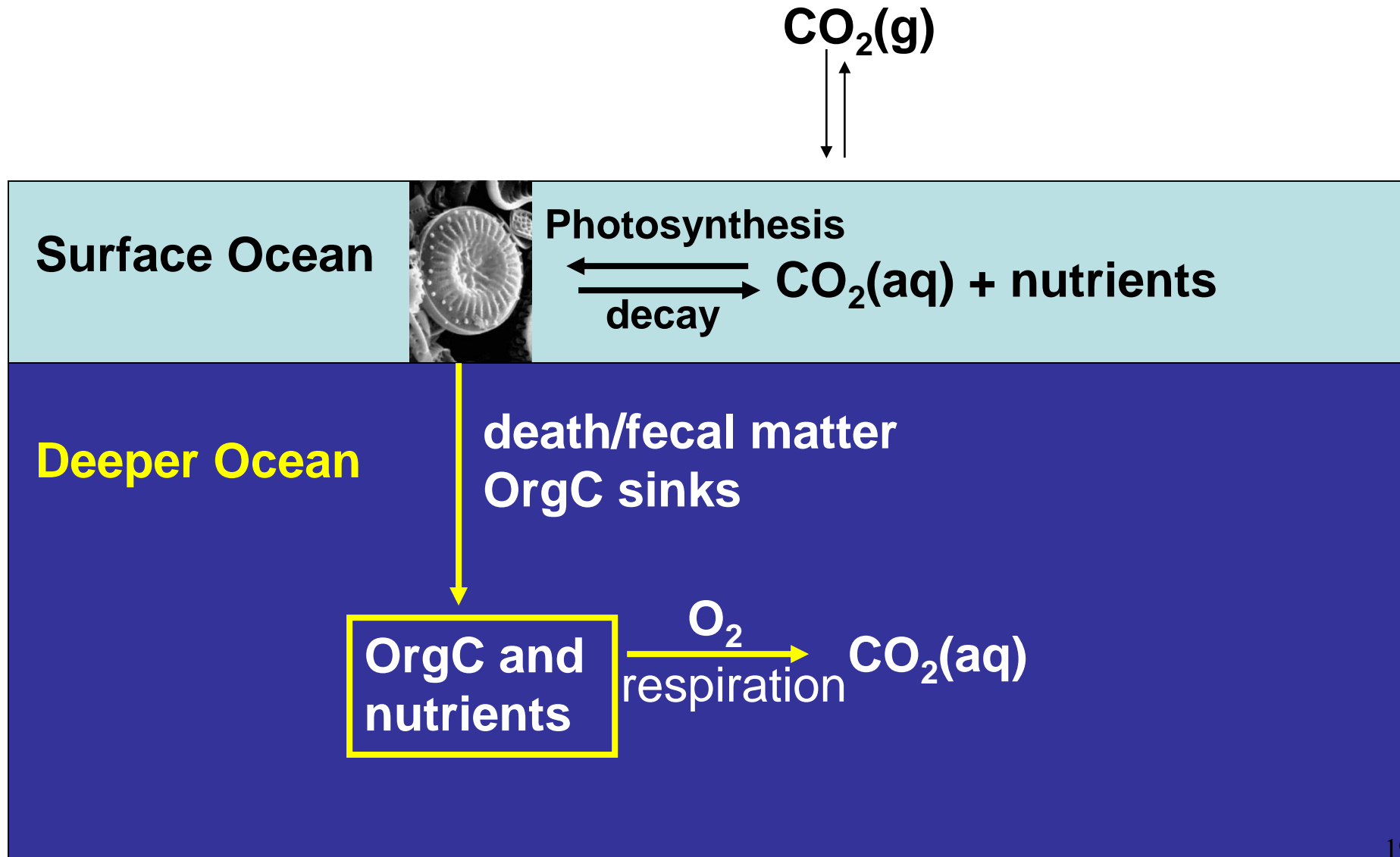
**$\text{CO}_2(\text{aq}) + \text{nutrients}$**

**Deeper Ocean**

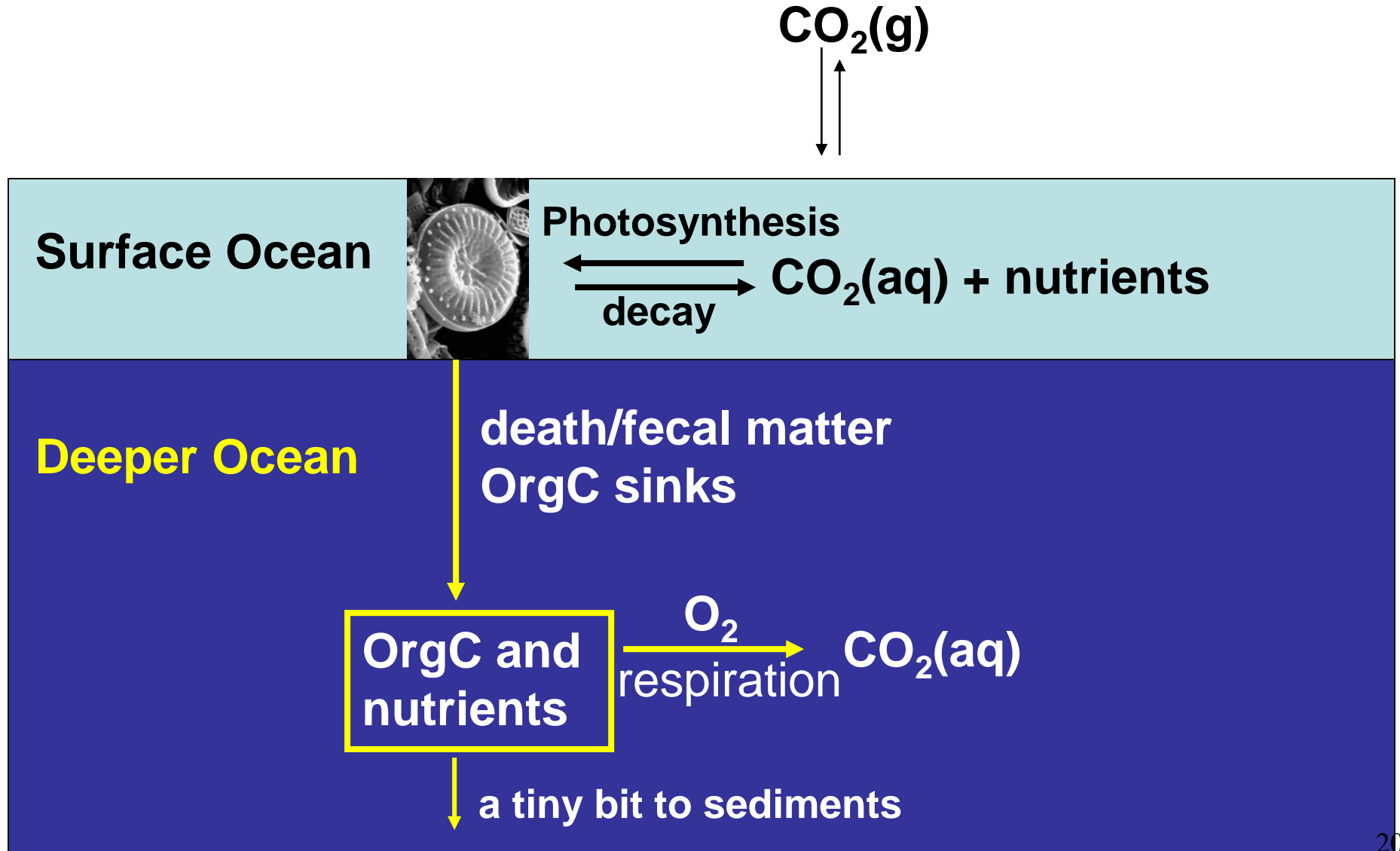
# Marine Organic C Cycle



# Marine Organic C Cycle

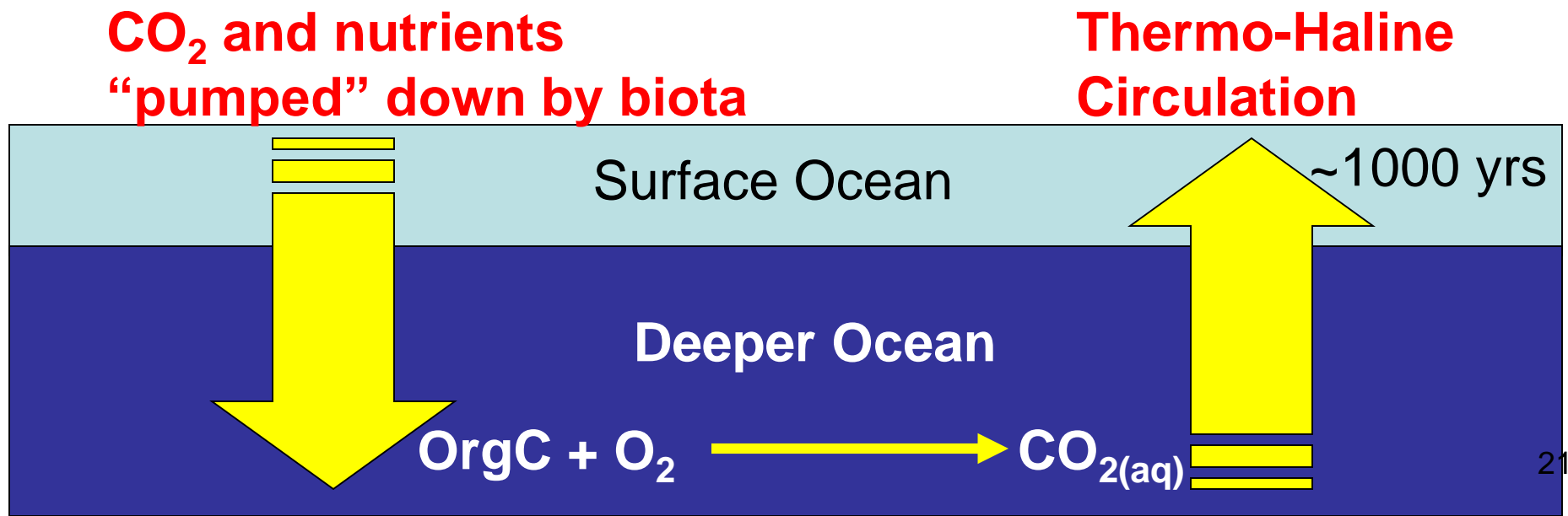


# Marine Organic C Cycle



# Marine Biological OrgC Pump: Key Points

1. Surface **depleted** (relatively) in C and nutrients
2. Deep ocean **enriched** in C and nutrients
3. Sinking of OrgC net pumps atm.  $\text{CO}_2$  into ocean  
—a net sink of  $\text{CO}_2$  on ~1000 year timescale



# Poll Question

W

Suppose global T decreases. This cooling leads to less precipitation (right?), less precipitation leads to drier soils and thus more windblown soil dust, which contains, Iron (Fe), a critical nutrient for phytoplankton.



When poll is active, respond at [Pollev.com/joelathornto254](https://Pollev.com/joelathornto254)



Text **JOELATHORNTO254** to **22333** once to join

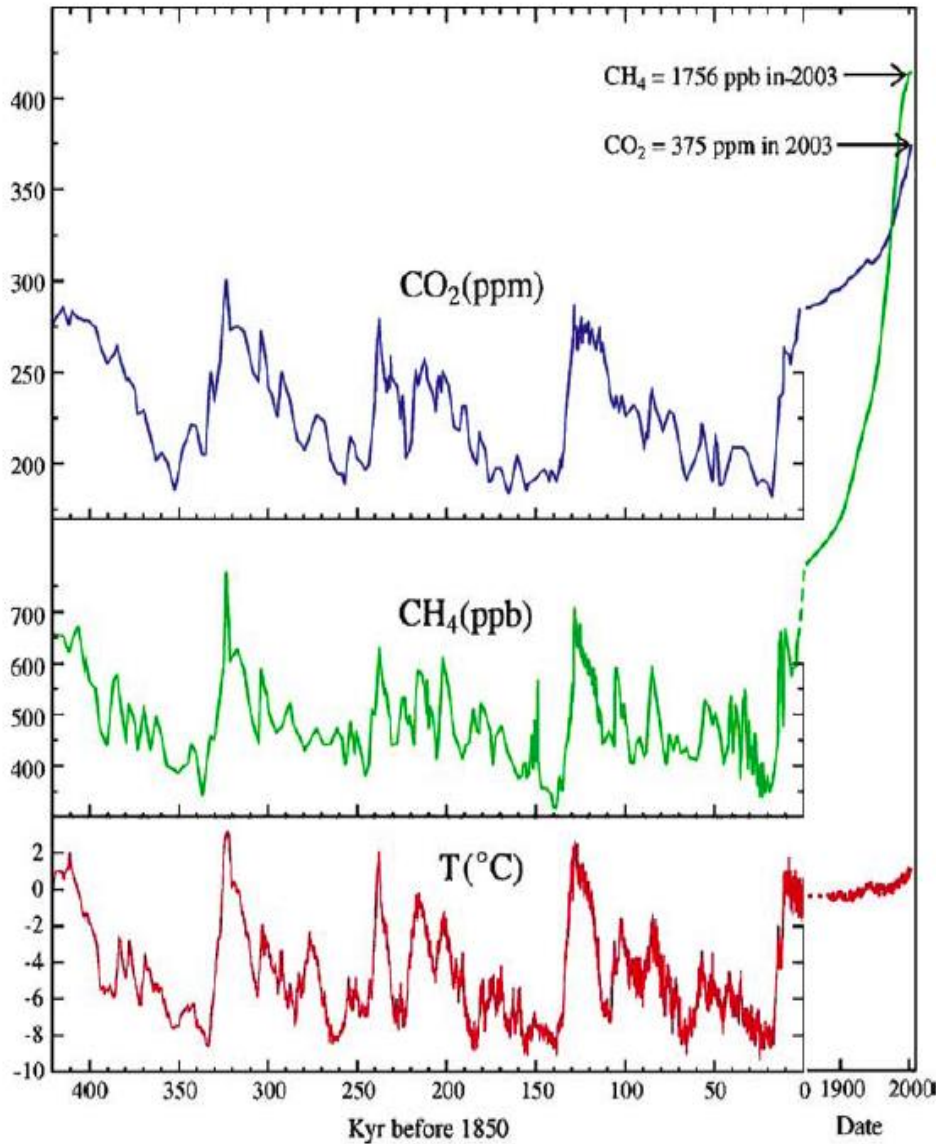
The biological pump causes a positive feedback

The biological pump causes a negative feedback



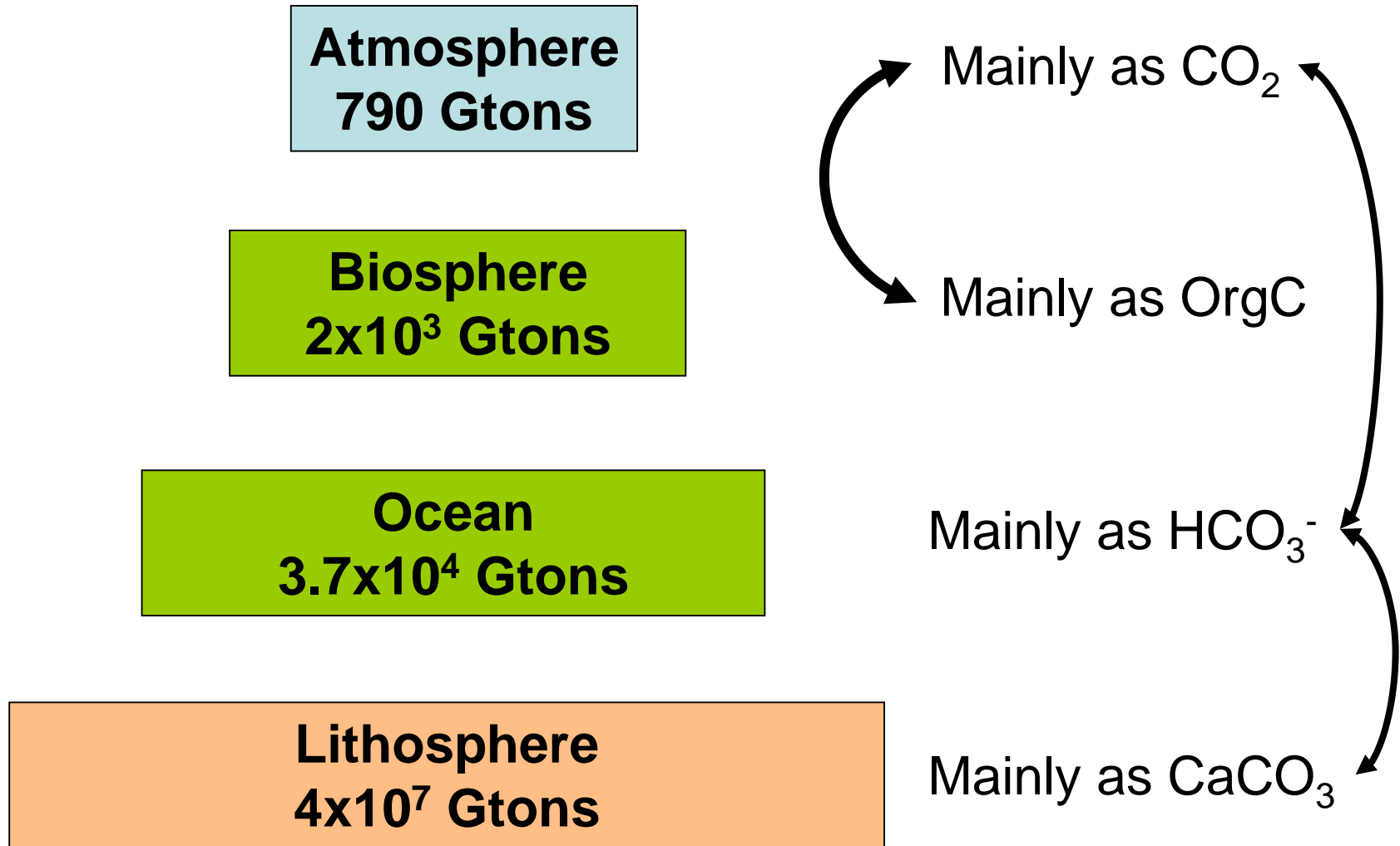
Total Results: 0

# Slow Carbon Cycles



Large (but slow)  
natural changes  
carbon

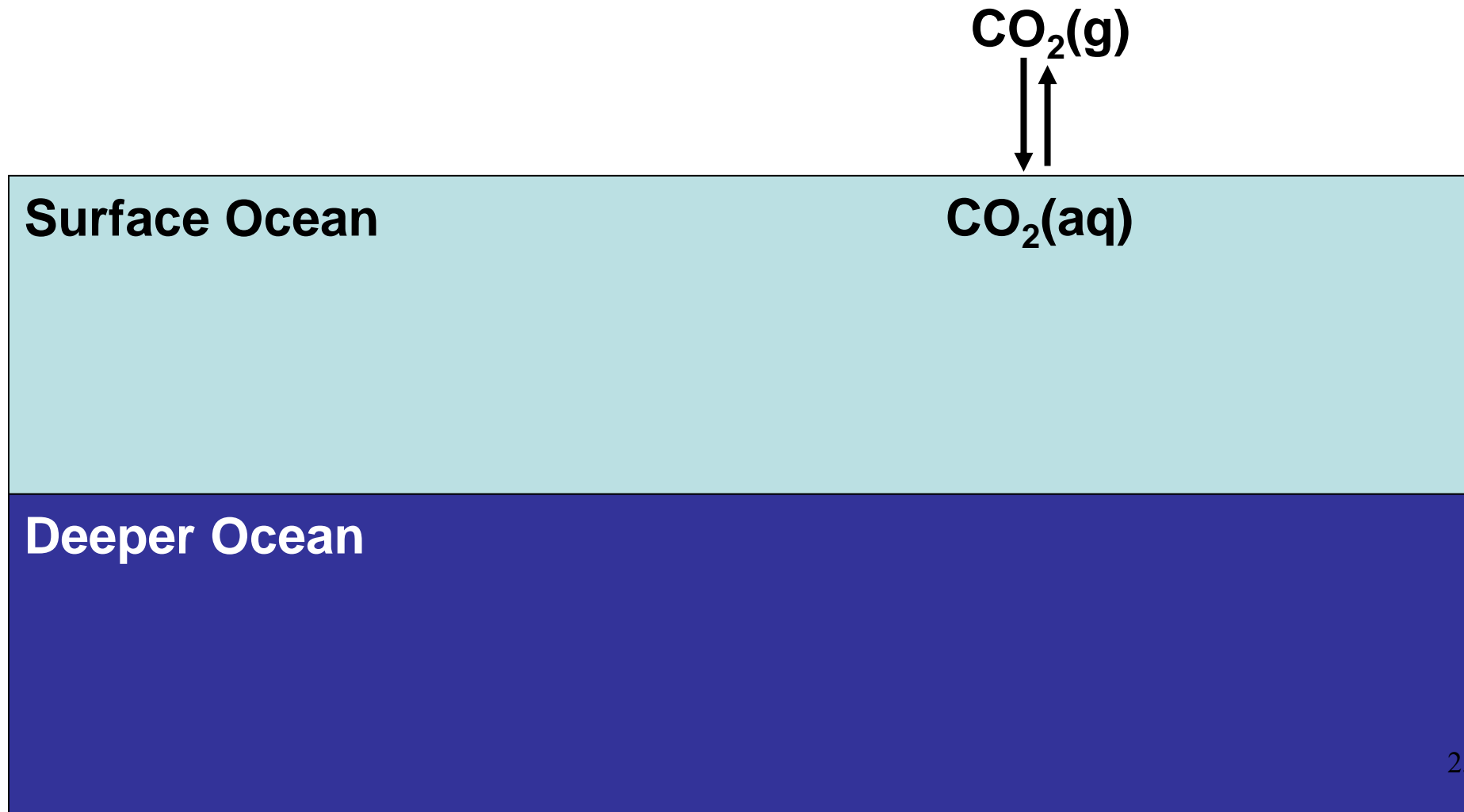
# Reservoirs of Carbon



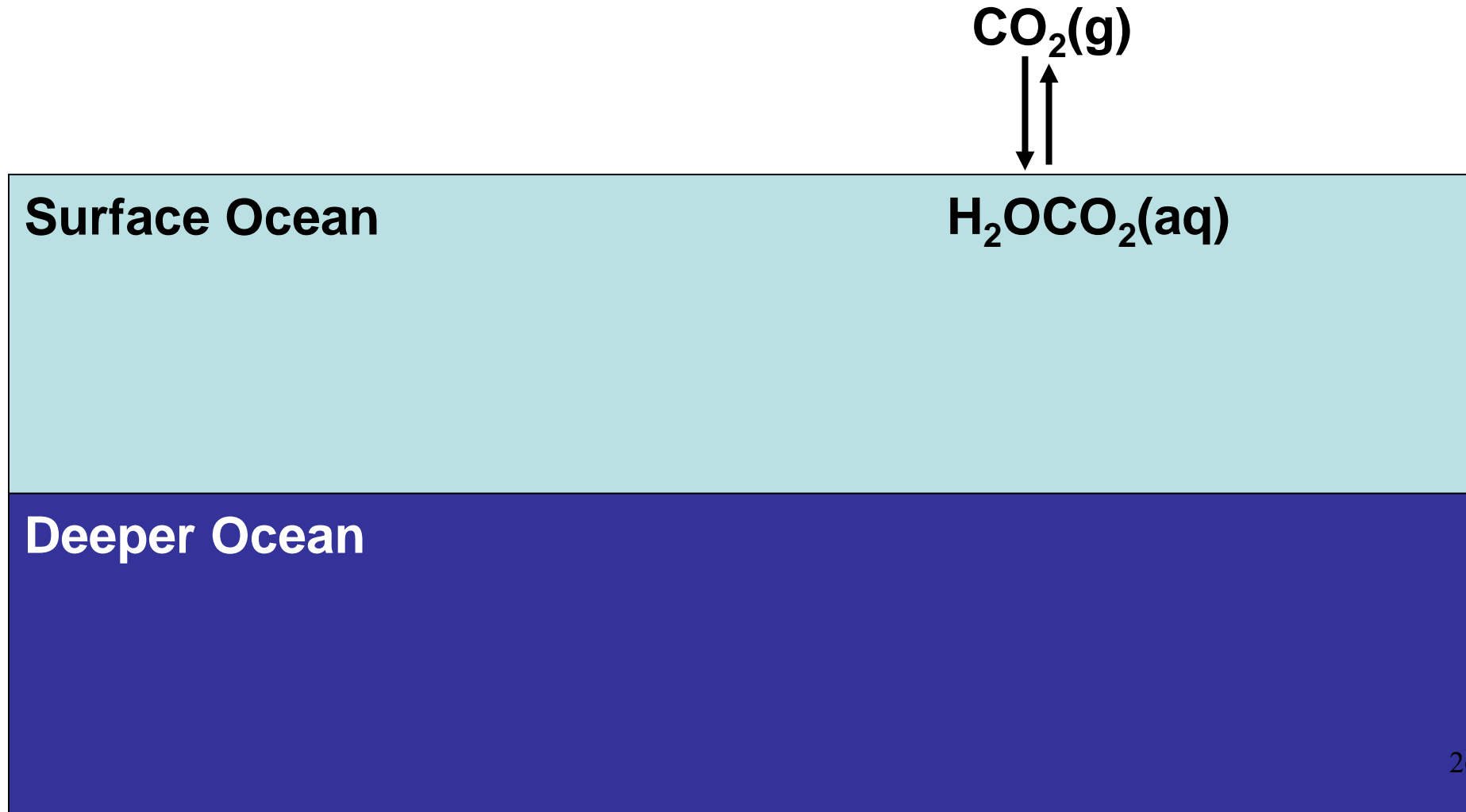
Carbon in the atmosphere and oceans mostly *inorganic*



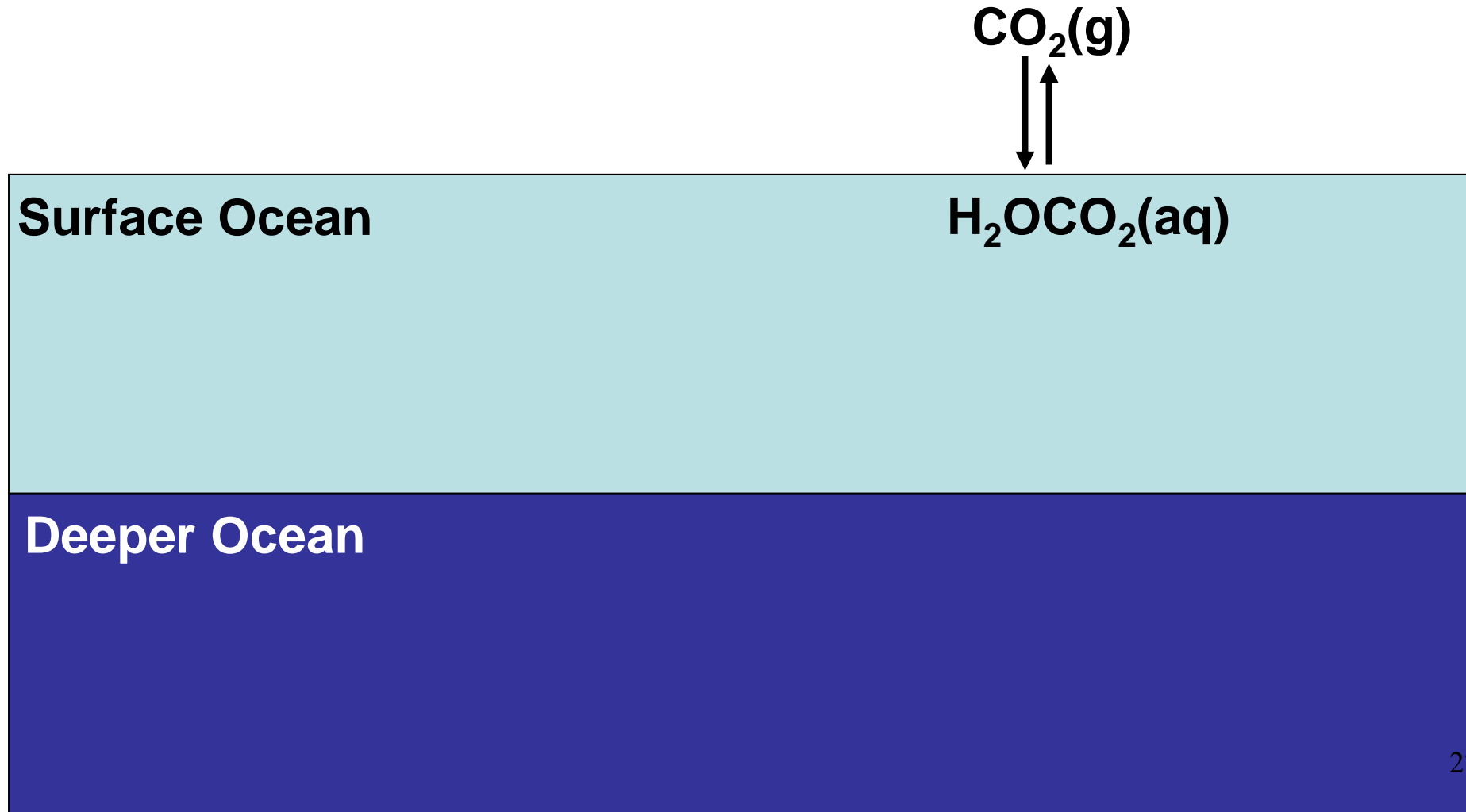
# CO<sub>2</sub> Dissolution Into Ocean Water



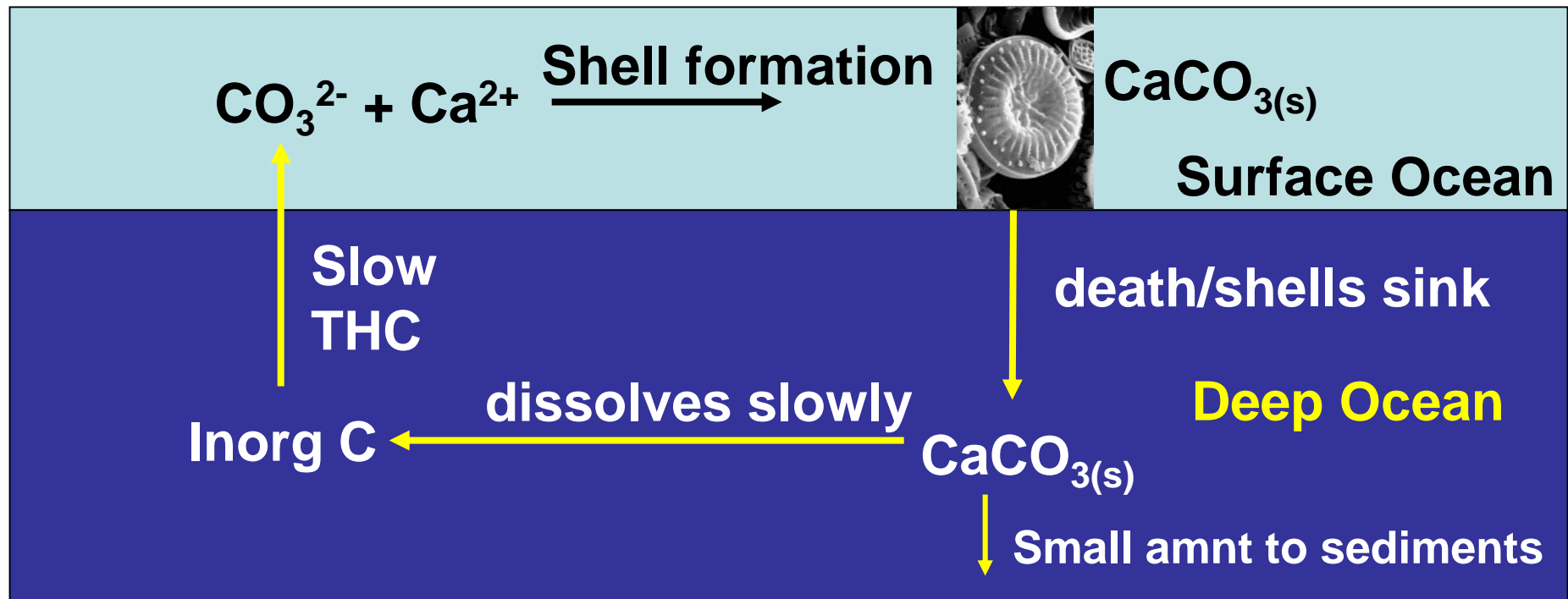
# CO<sub>2</sub> Dissolution Into Ocean Water



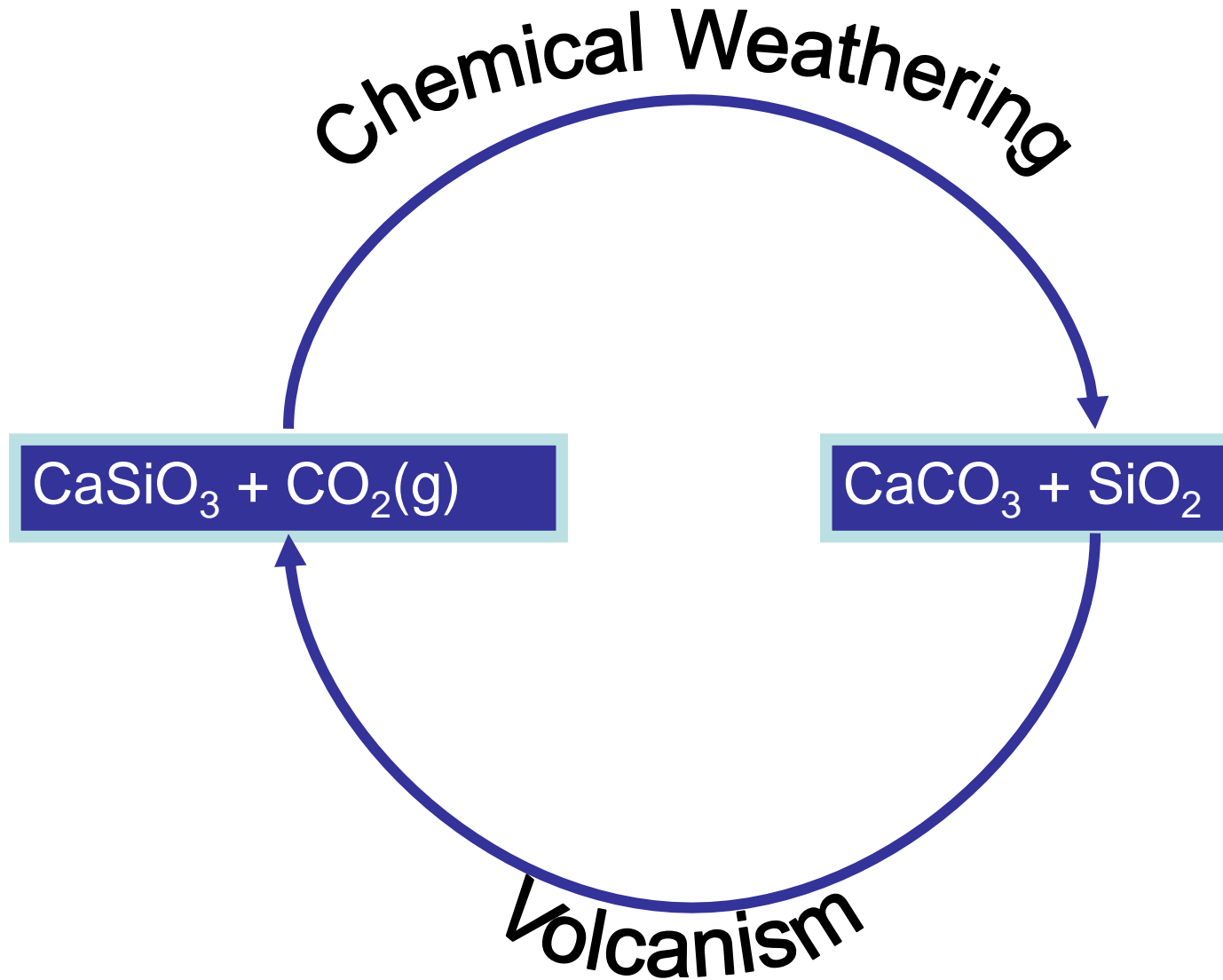
# CO<sub>2</sub> Dissolution Into Ocean Water



# Shell Formation (A Short-term InorgC Cycle)



# The “Ultimate” InorgC Cycle



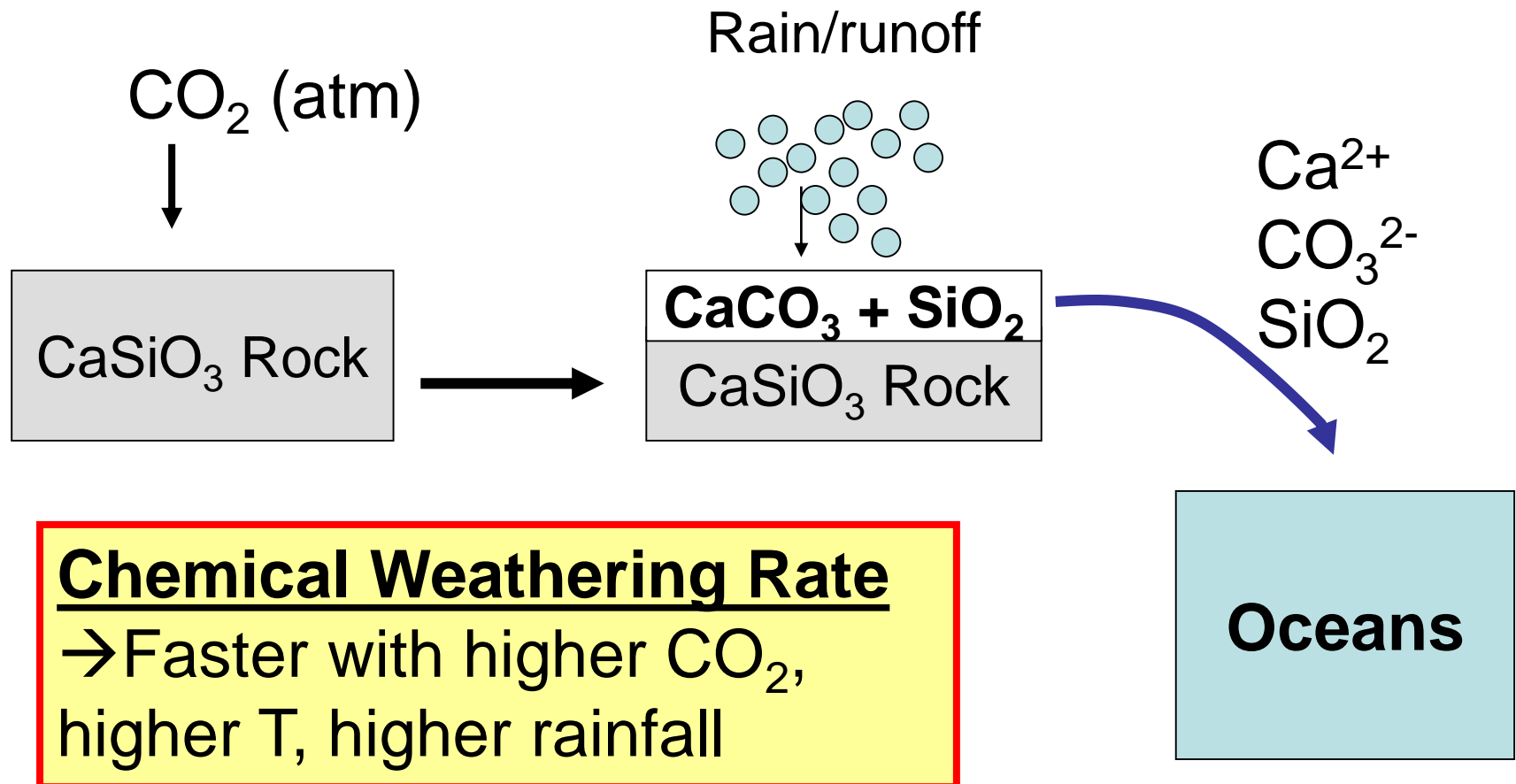
# Weathering and Volcanism: Rocks Do Chemistry

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# Example of Weathering ( $\text{CaCO}_3$ dissolution)



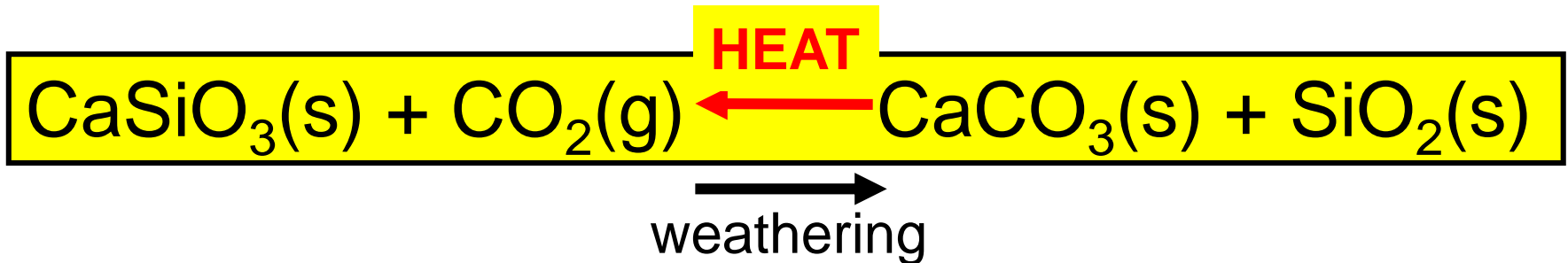
# Silicate Weathering (simplified)





# Volcanic Degassing

**Volcanism causes reverse of weathering**



**Tectonic activity converts  $\text{CaCO}_3$  rocks back to silicate rocks ( $\text{CaSiO}_3$ ) in the mantle (magma).**

**Released  $\text{CO}_2$  finds way to atmosphere via vents**

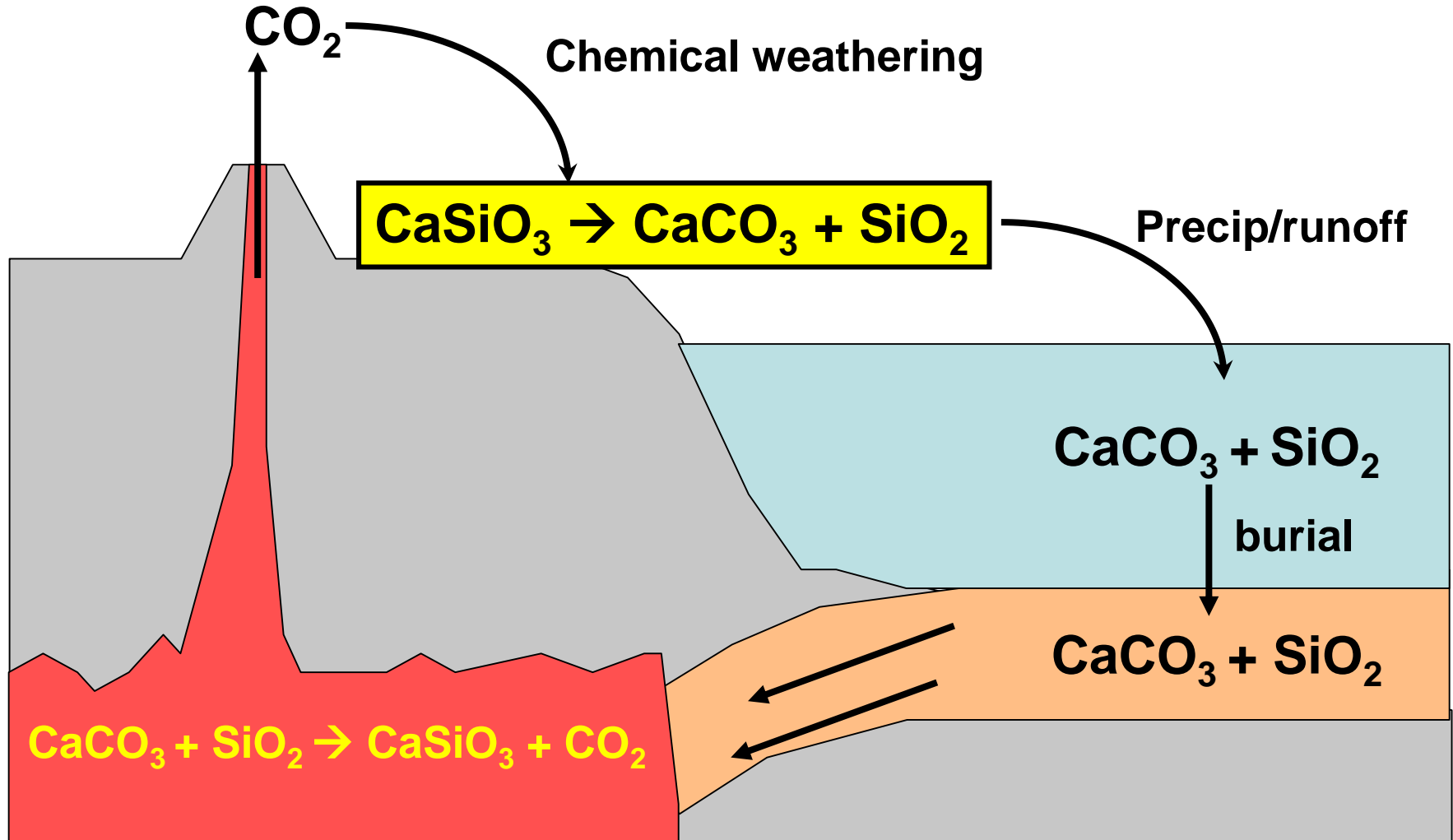
# Volcanism in Action



May 4 2018



# Silicate Weathering – Volcanism Cycle



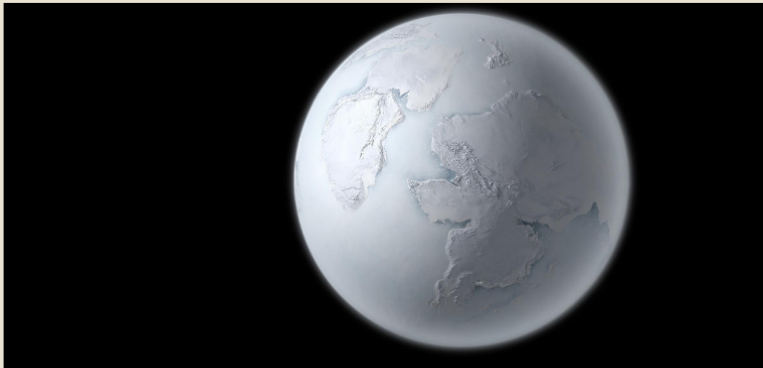
This cycle operates on 0.5 – 1 million year timescale.

# Poll Question

# W

Suppose there a massive ice age, where land oceans largely froze over...

 **Poll locked.** Responses not accepted.




The reduced water vapor and precipitation, and enhanced albedo would prevent recovery, and thus, unlikely to have happened

The weathering rate would slow, while volcanism and plate tectonics continued, causing an eventual melting back to a warm climate, and thus may have happened (or happen at some point)

Visual settings 

Activate 


Show results 

Show correct 

Lock 

Clear results 

Fullscreen 

Next 

Previous 

# Silicate Weathering Feedback

**Atmospheric  
CO<sub>2</sub>**

**Silicate  
Weathering Rate**

**Temperature/  
Precipitation**

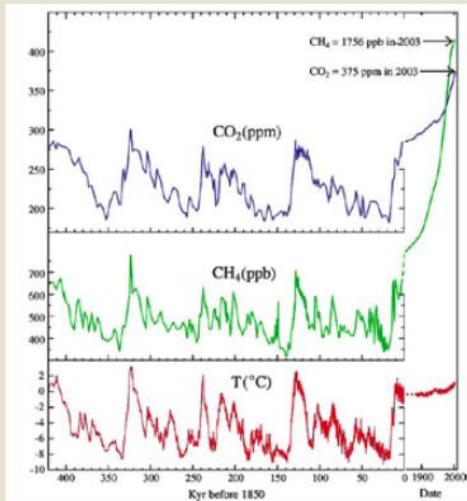
# Poll Question

W

Does the silicate weathering feedback loop explain the glacial-interglacial cycling of atmospheric CO<sub>2</sub>?

When poll is active, respond at [Pollev.com/joelathornto254](https://Pollev.com/joelathornto254)

Text **JOELATHORNTO254** to **22333** once to join



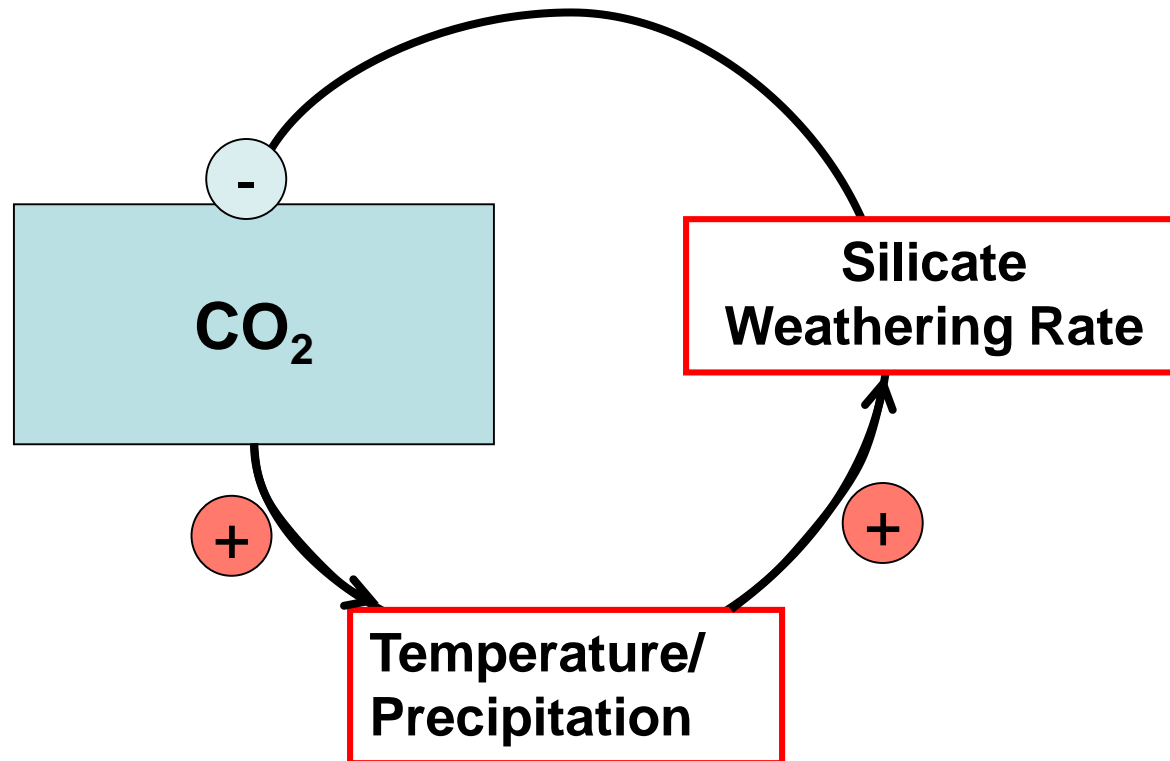
Yes

No

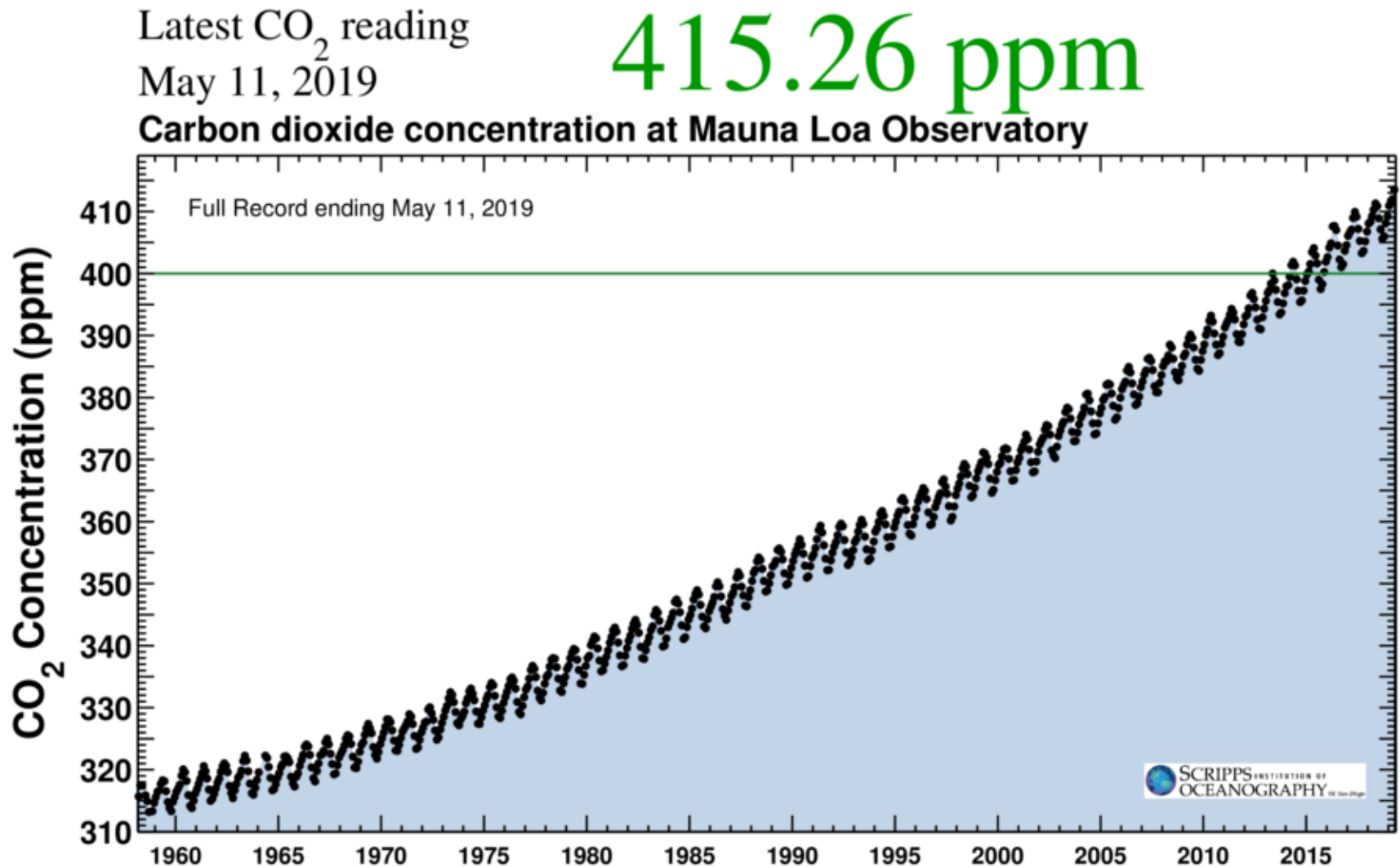
Total Results: 0

# Silicate Weathering Feedback

**Negative Feedback—Stabilizing Climate**  
(on *long time* scales 0.5 to 1 million years)



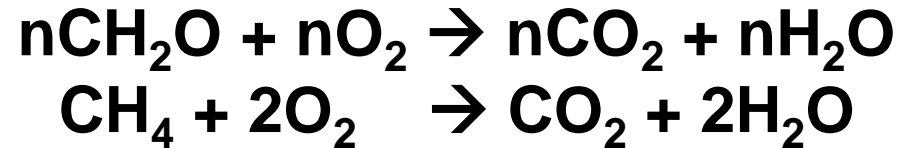
# Anthropogenic Perturbations to Carbon Cycle





# Atmospheric CO<sub>2</sub> and Source Attribution

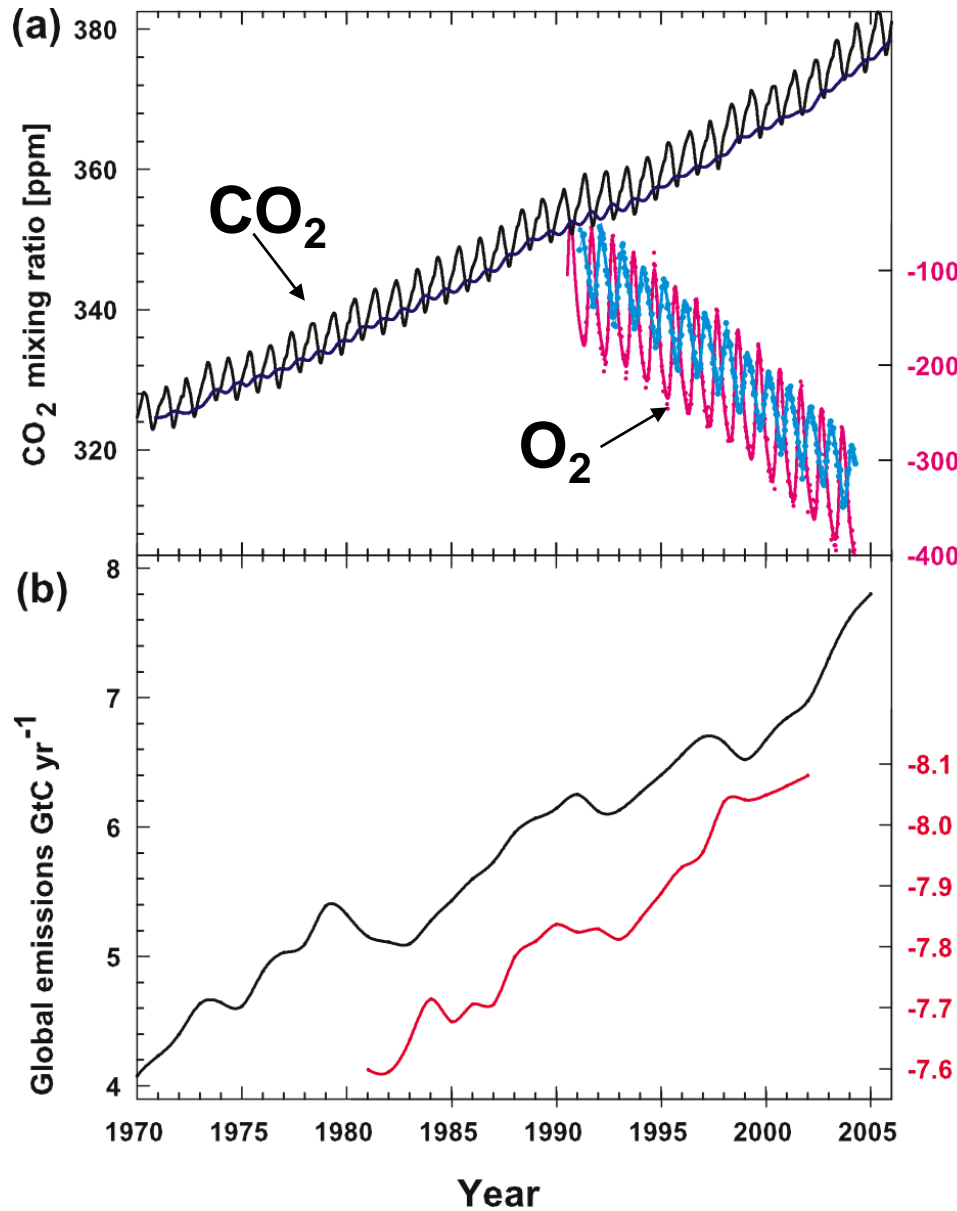
## Fuel Combustion:



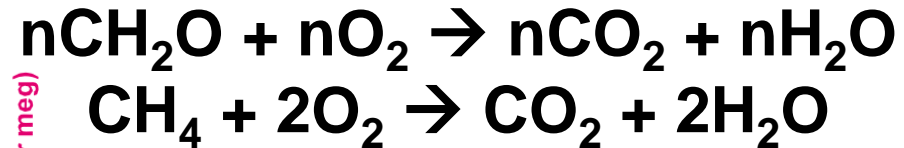
If CO<sub>2</sub> increase is due to  
fuel burning...

→ O<sub>2</sub> should decrease!

# Atmospheric CO<sub>2</sub> and Source Attribution



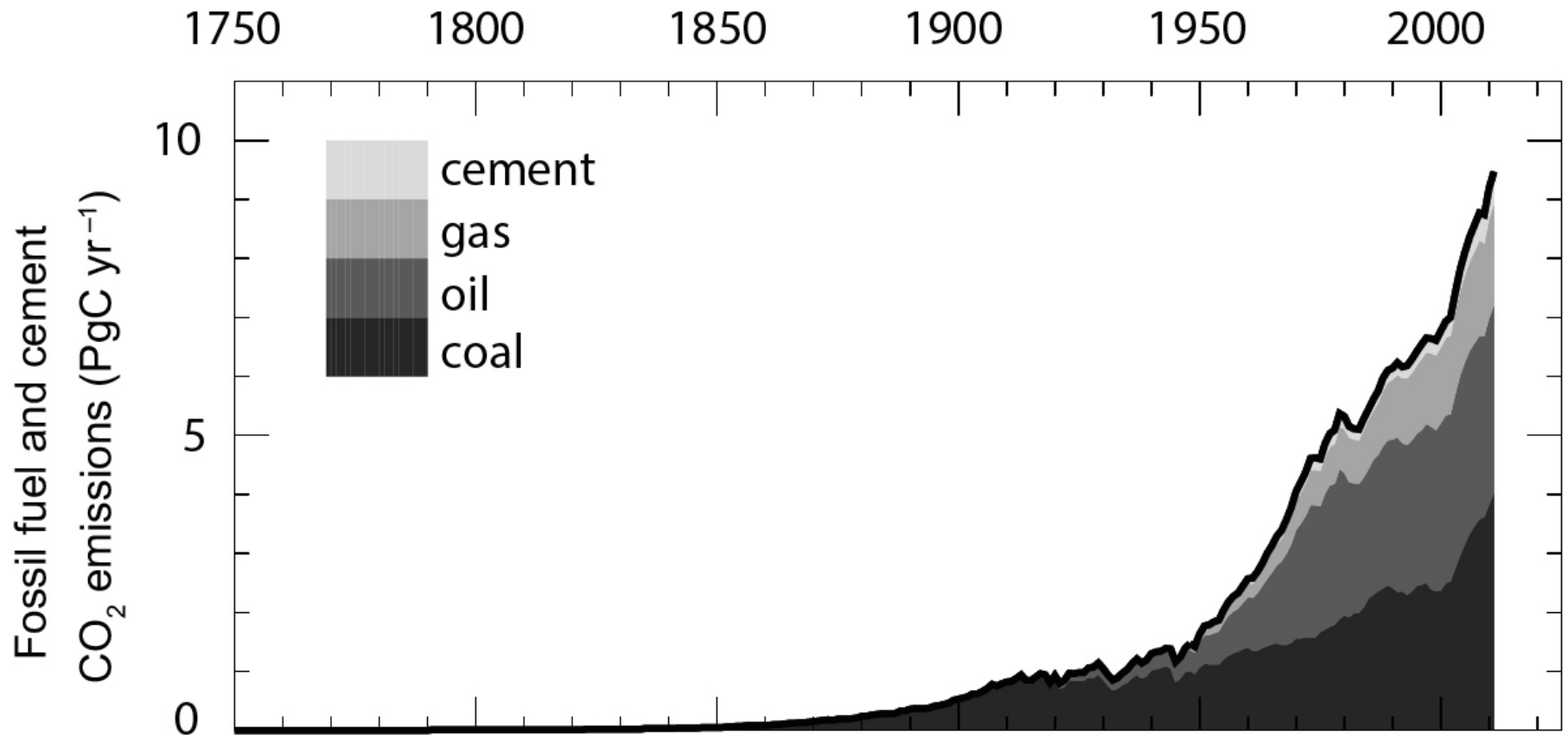
## Fuel Combustion:



If CO<sub>2</sub> increase is due to fuel burning...

→ O<sub>2</sub> should decrease!

# Anthropogenic Perturbations to Carbon Cycle

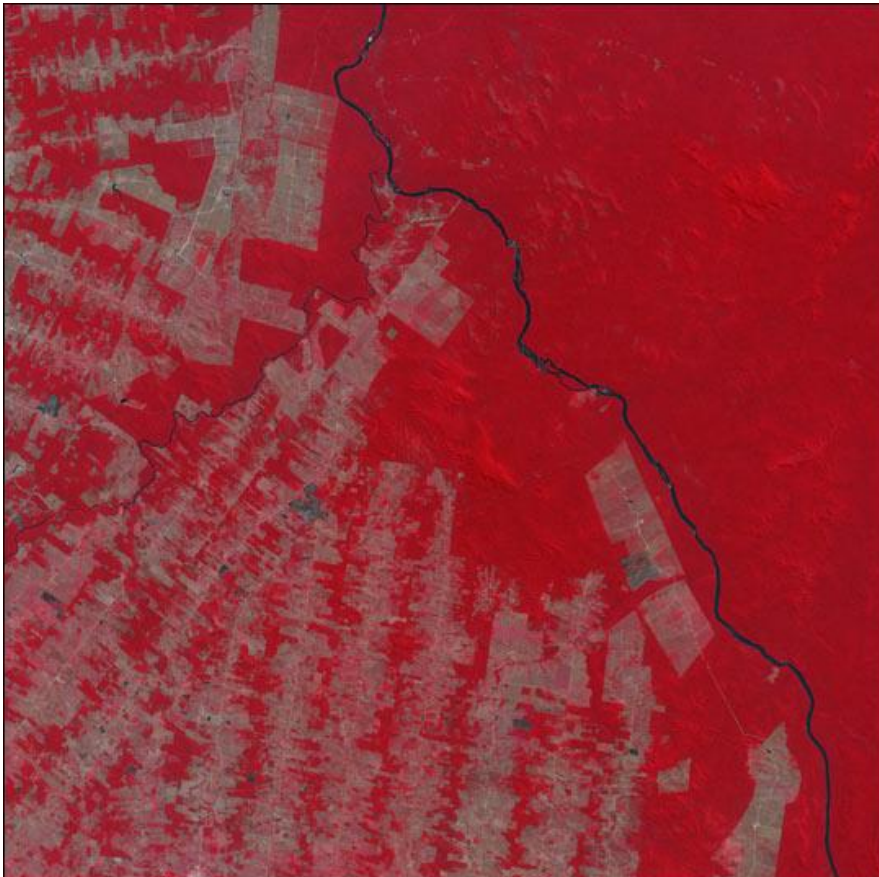


IPCC 2014

# Human Perturbations to Carbon Cycle

**Fossil Fuel Combustion ~ 8 GtC/yr currently**

**Deforestation ~ 2 GtC/yr (mostly in tropics)**



# Poll Question

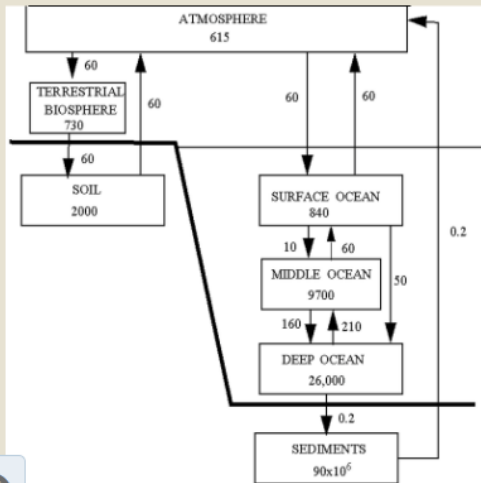
**W** Fossil fuel burning by humans injects ~ 8 Gt C per year into the atmosphere as CO<sub>2</sub>, which is a \_\_\_ over the natural input rate of Carbon from the sediments to the atmosphere.



When poll is active, respond at [PollEv.com/joelathornto254](https://pollev.com/joelathornto254)



Text **JOELATHORNTO254** to **22333** once to join



4-fold increase

10-fold increase

40-fold increase

Total Results: 0

# Poll Question

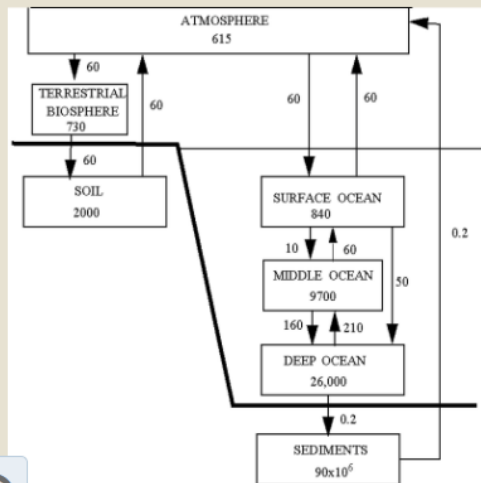
**W** If we ceased fossil fuel burning and deforestation, how long would it take the Earth system to fully recover from our current perturbation?



When poll is active, respond at [PollEv.com/joelathornto254](https://pollev.com/joelathornto254)



Text **JOELATHORNTO254** to **22333** once to join



Decades

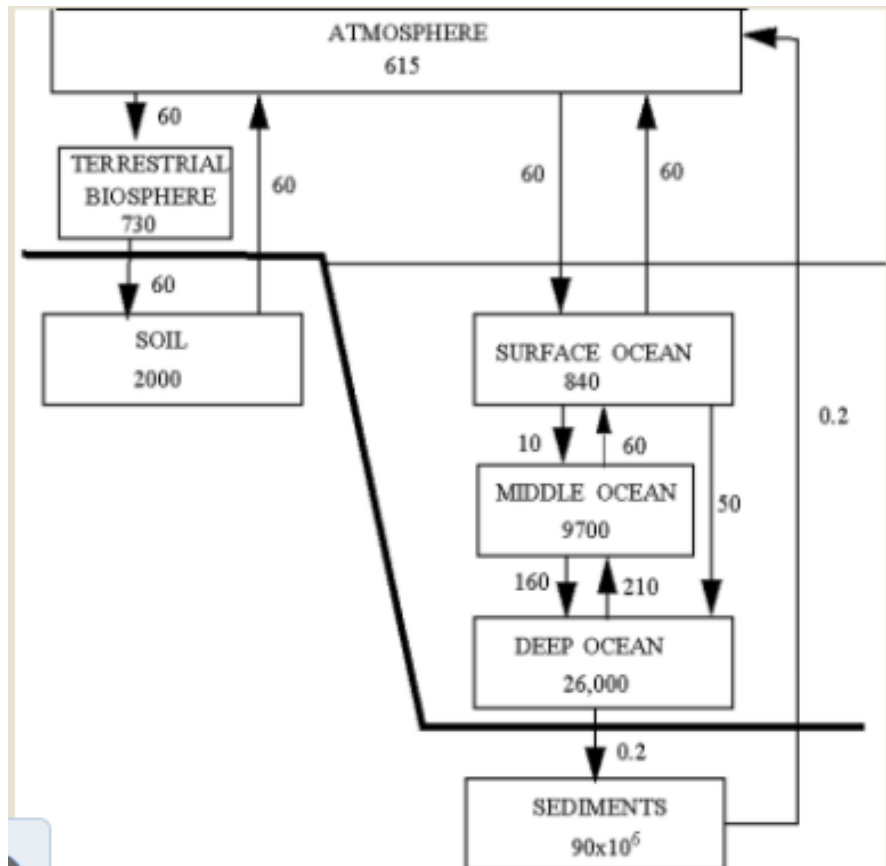
Centuries

Millenia

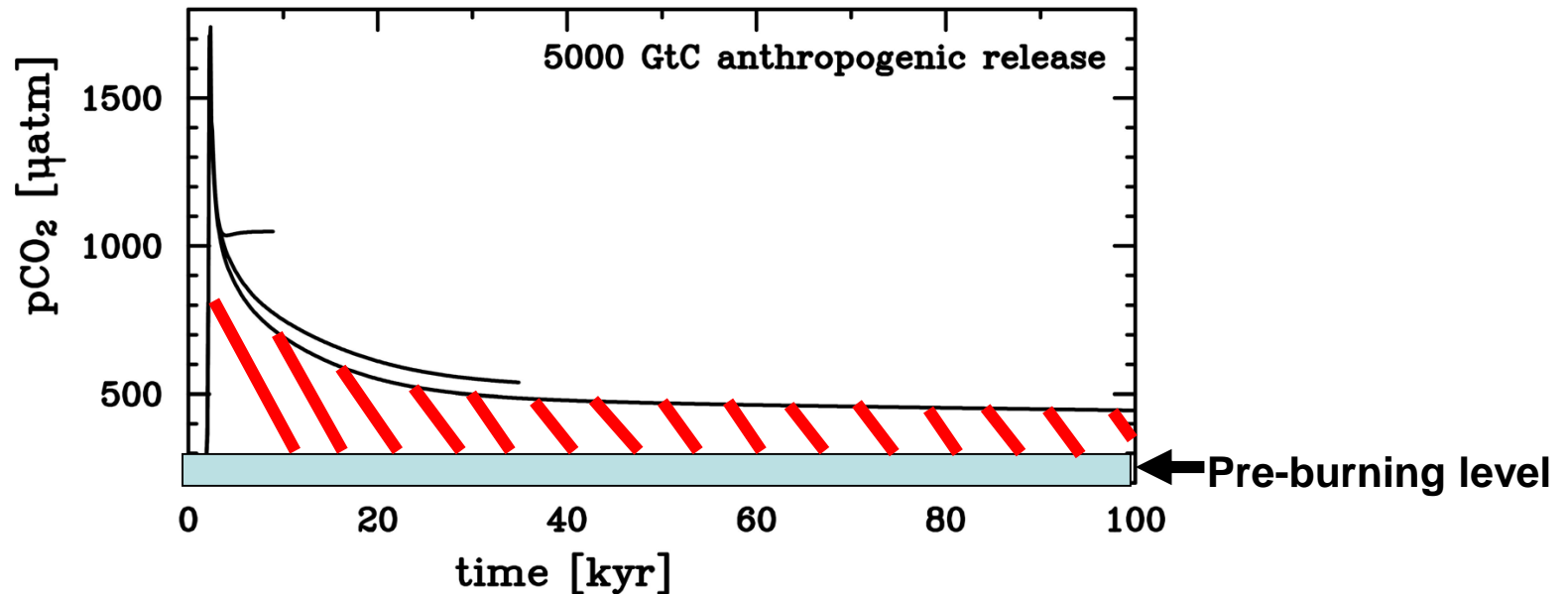
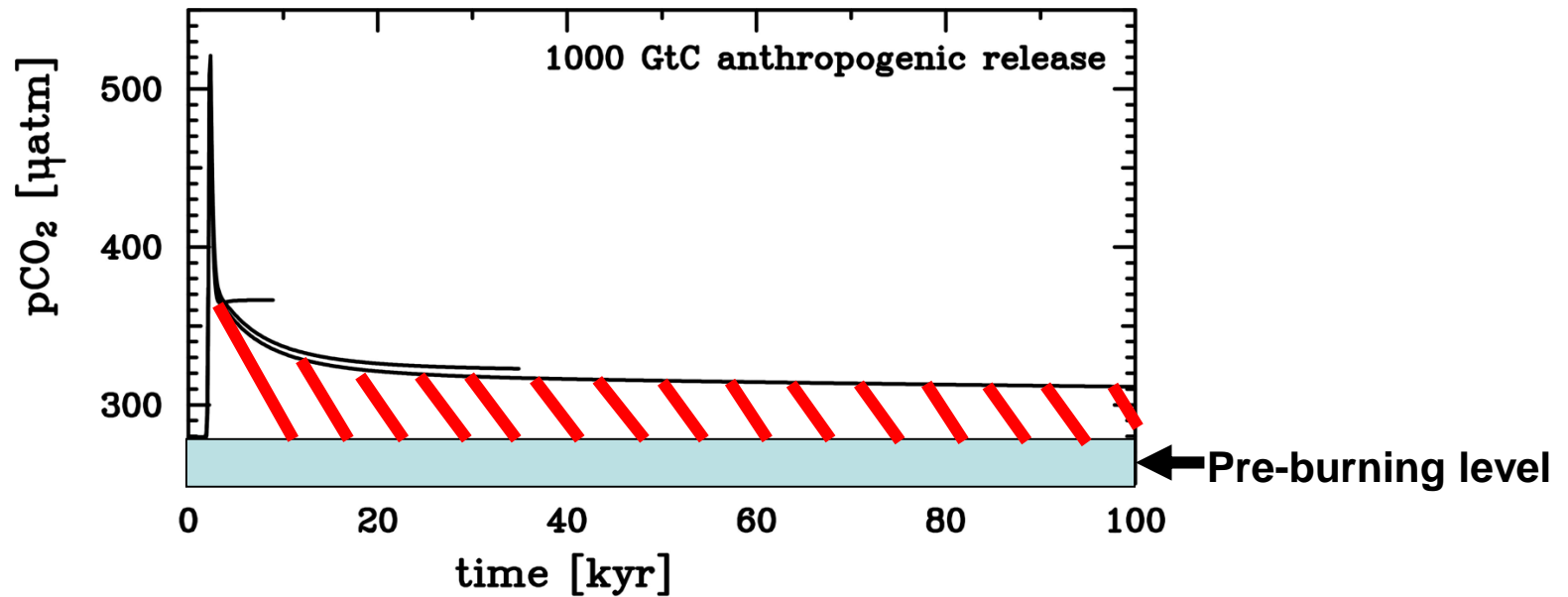
>100,000 years

Total Results: 0

# Anthropogenic Perturbation to C cycle



# A Long View of Fossil Fuel Perturbation



Adapted From: Archer, *J. Geophys. Res.*



W

Fossil fuel usage statistics and land use change suggest CO<sub>2</sub> emissions of approximately 8 GtC/year on average over the past couple decades, while atmospheric CO<sub>2</sub> measured at Mauna Loa increased by about 2 ppm/year on average, which is ~4 GtC/year.

Visual settings 

Activate 

Show results 

Show correct 

Lock 

Clear results 


Fullscreen 


 **Poll locked.** Responses not accepted.

Anthropogenic CO<sub>2</sub> emissions are likely overestimated by about 50%

Atmospheric CO<sub>2</sub> could be even higher than it is, but about 50% of what is added is being removed from the atmosphere each year

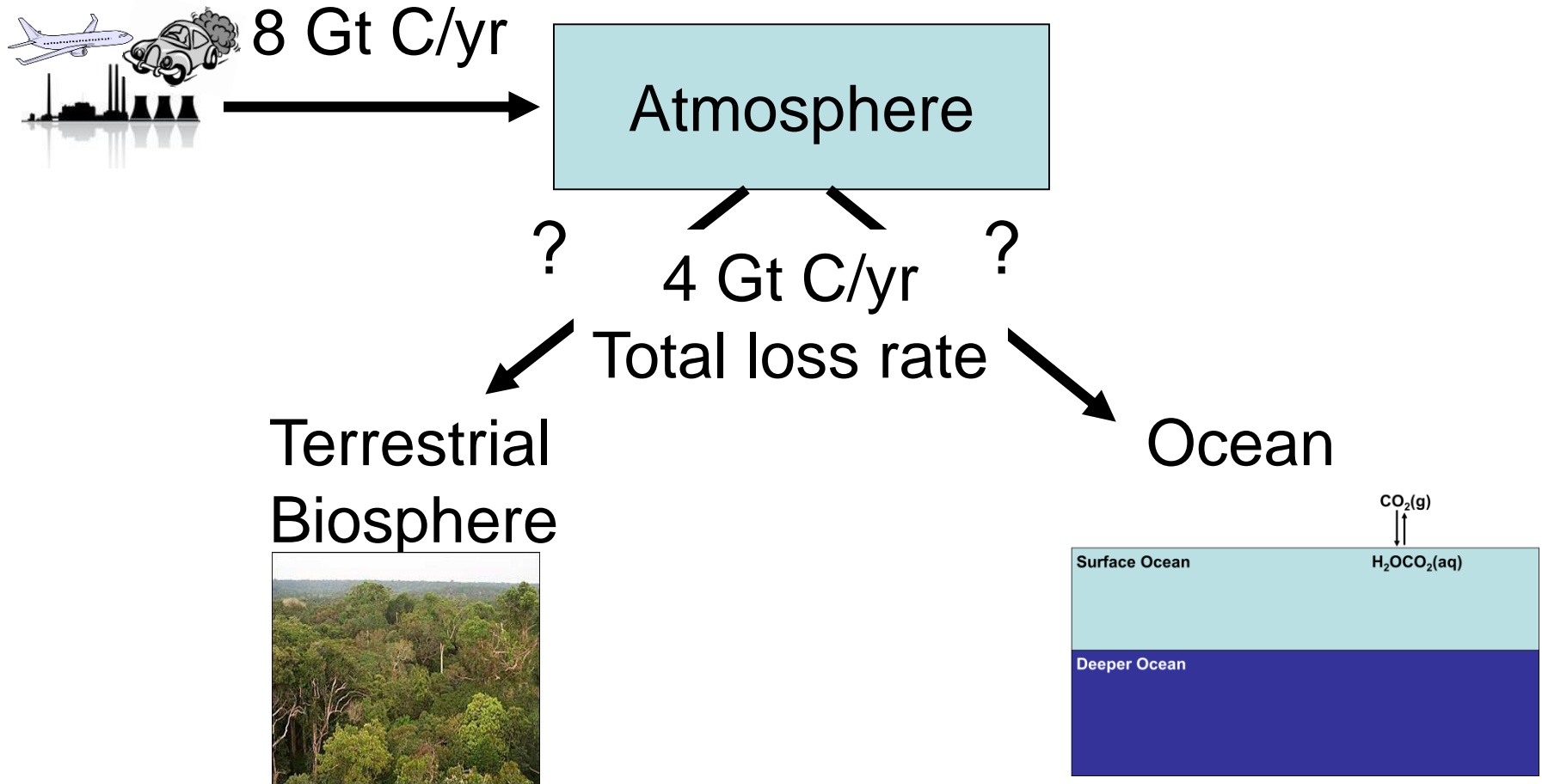
Mauna Loa trends are not representative of the global atmospheric CO<sub>2</sub>

Next 

Previous 

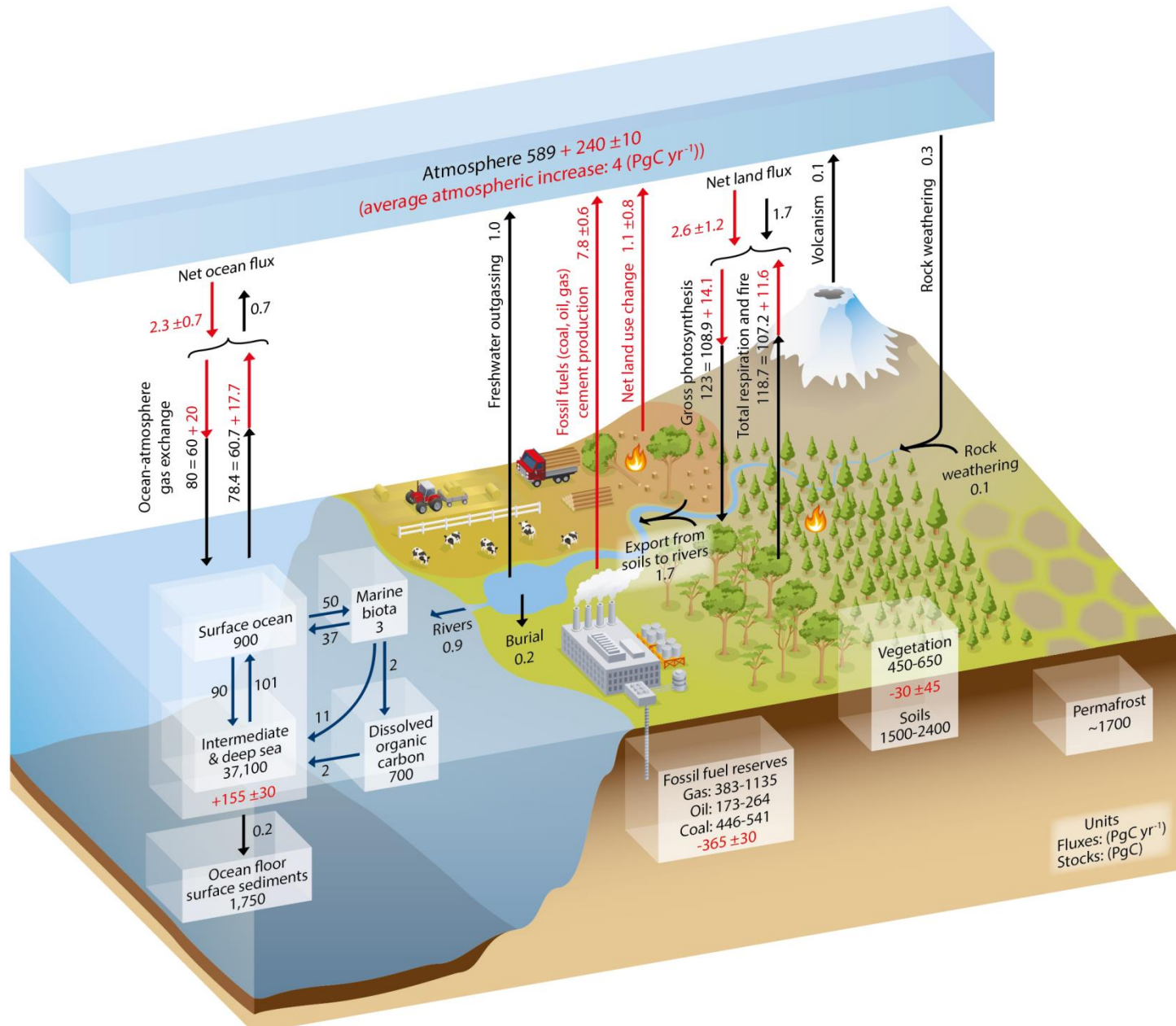
Total Results: 0

# Present Day CO<sub>2</sub> Sources and Sinks

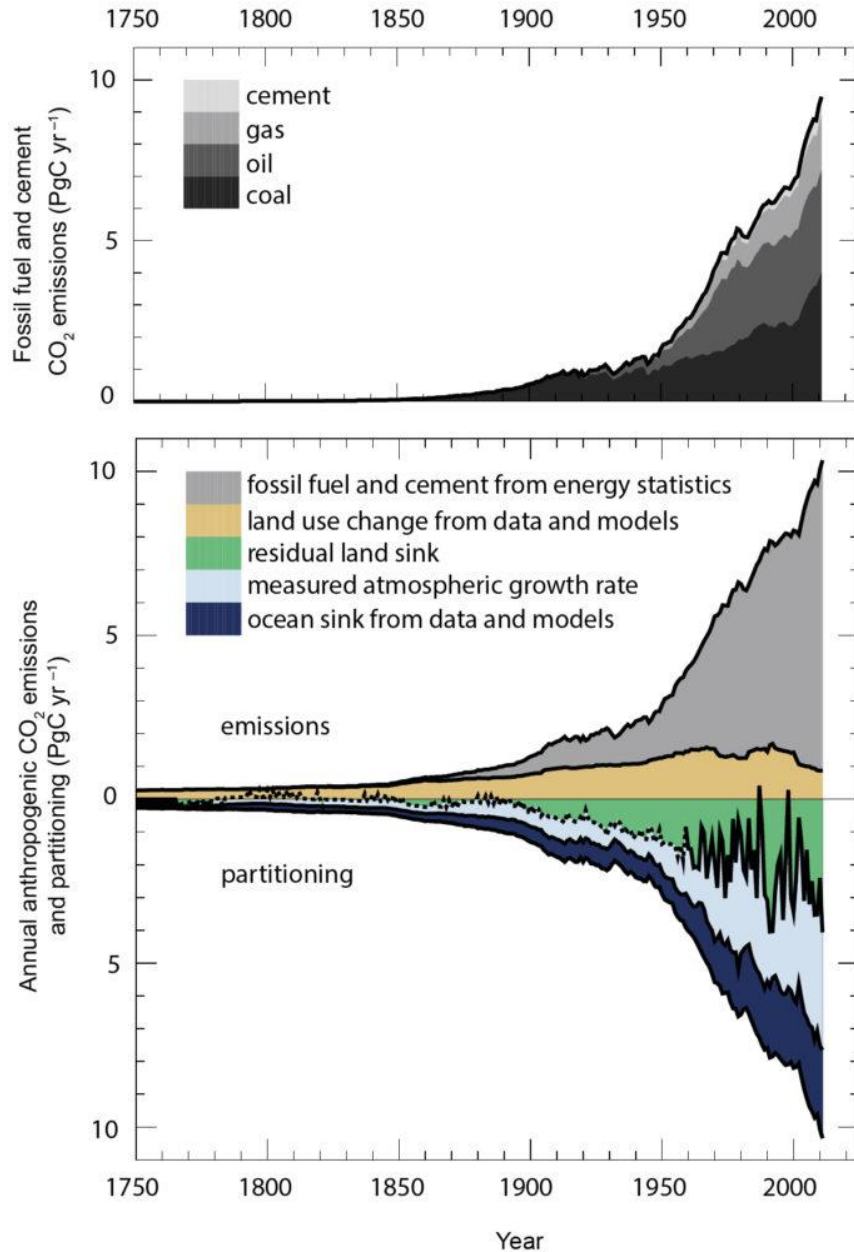


Where is the 4 GtC going each year?

# Natural and Perturbed Carbon Cycle

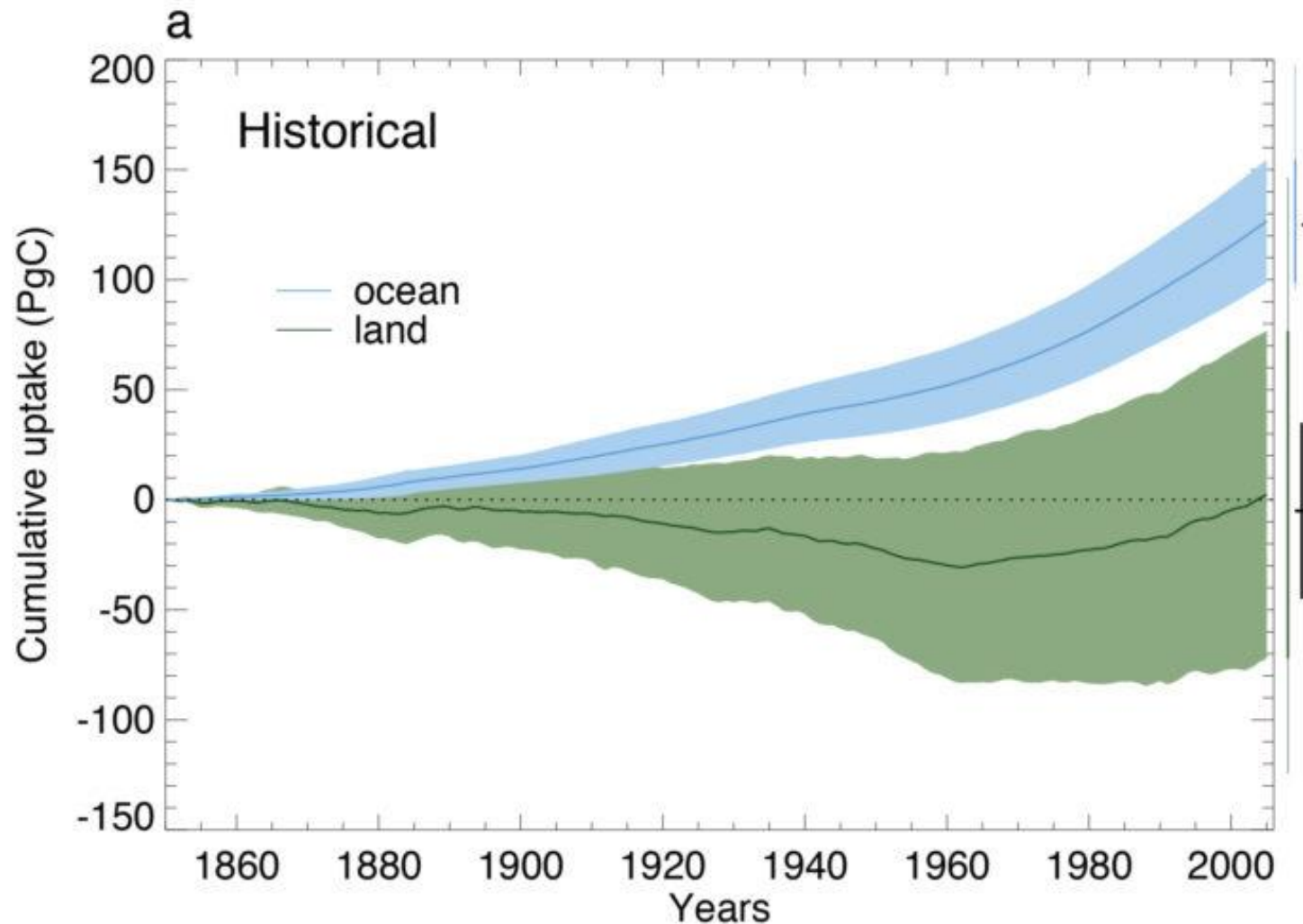


# Atmospheric CO<sub>2</sub> sources and sinks

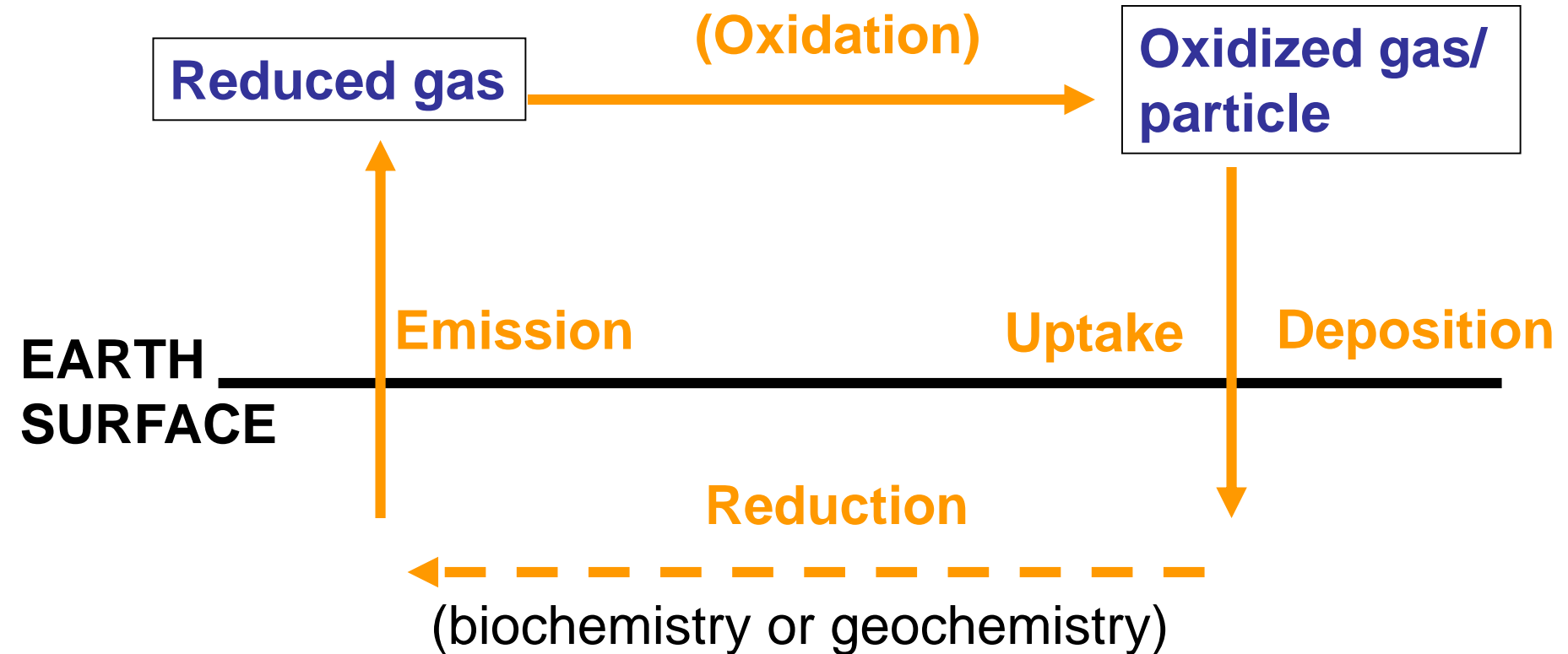


- **Where is fossil fuel C going?**

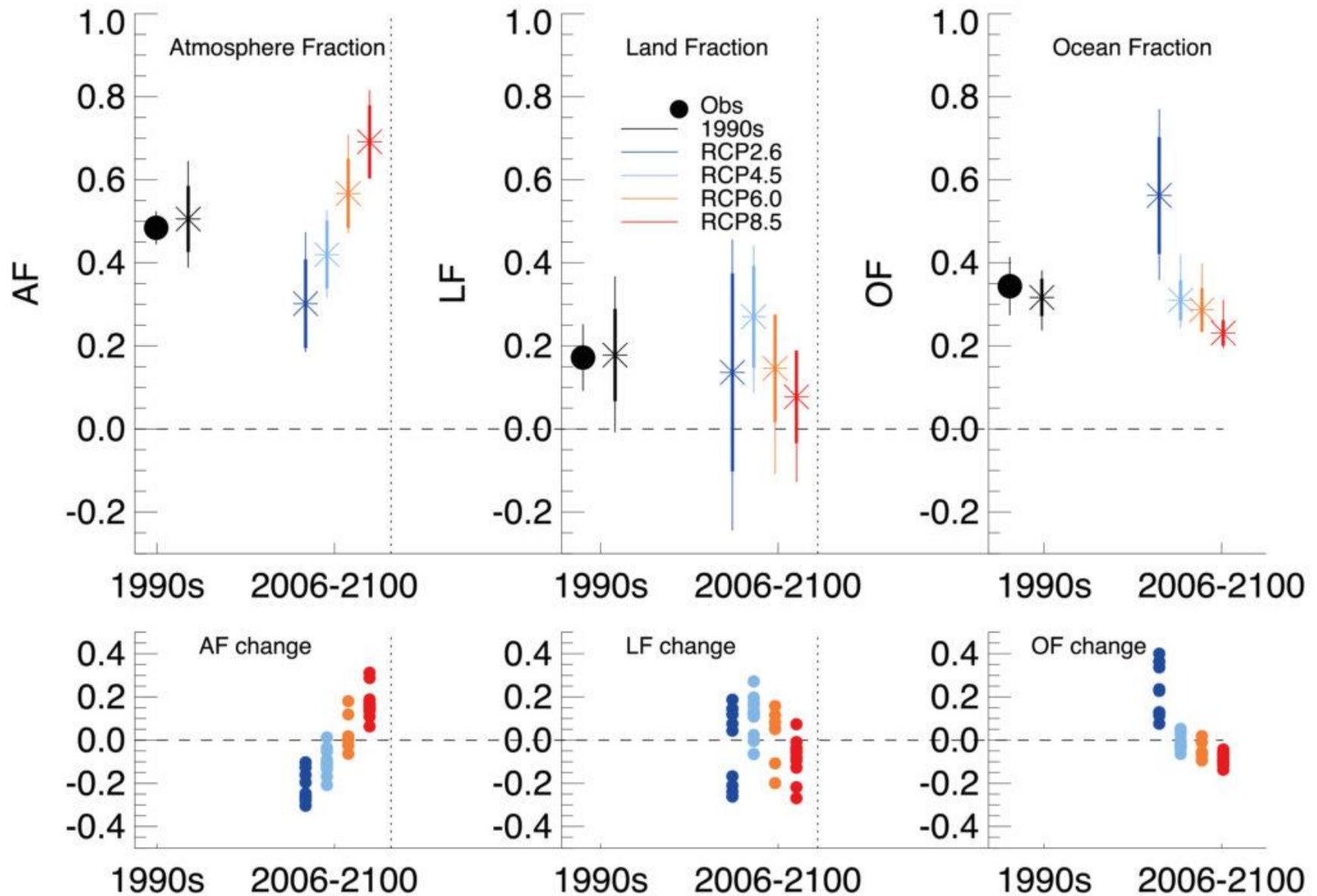
# Ocean and Terrestrial Removal of Atmospheric C



# Global Biogeochemical Cycles: Future??

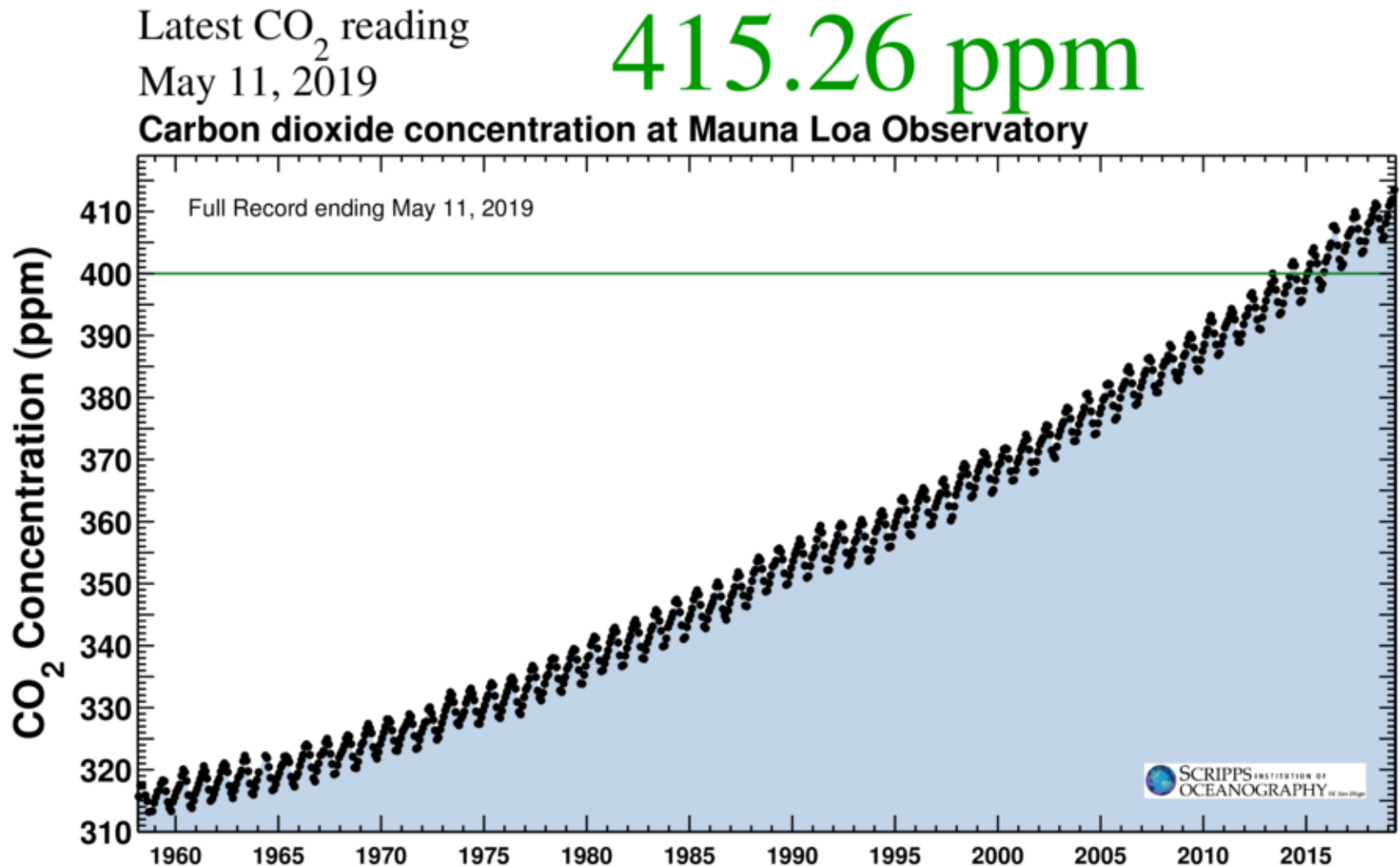


# Future Land and Ocean Sinks Predicted to Decrease





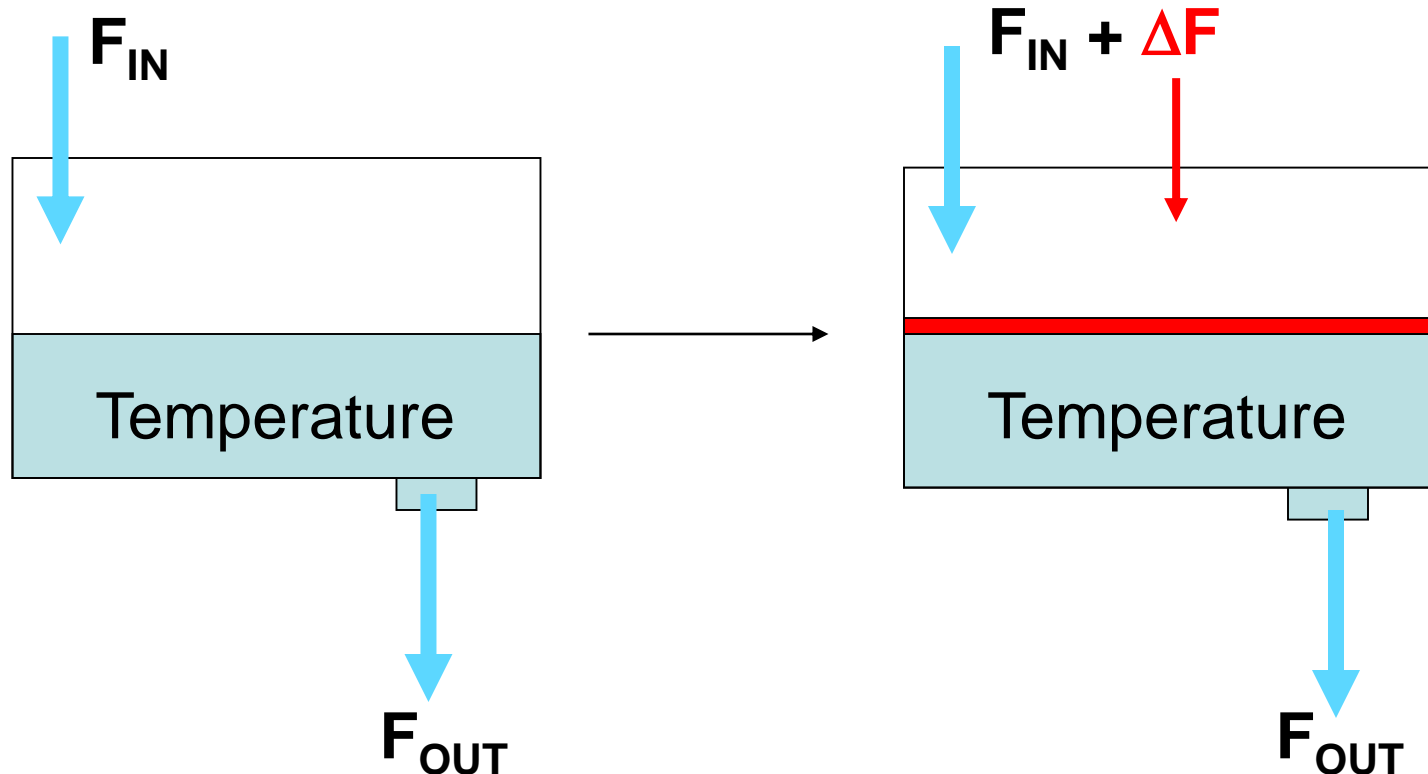
# Anthropogenic Perturbations to Carbon Cycle





# Climate Forcings

a perturbation that directly or indirectly affects Earth's energy budget



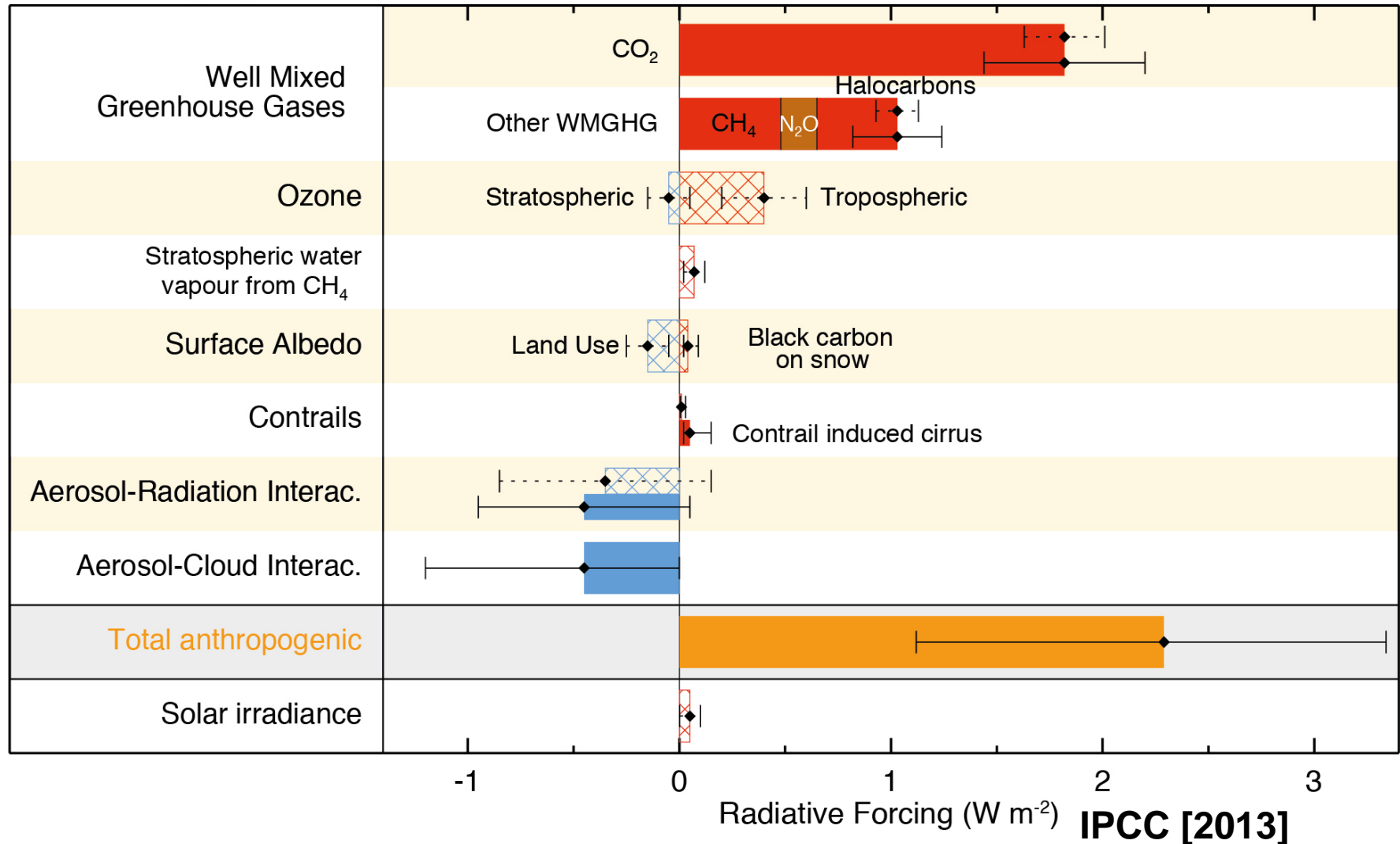
# Radiative Forcings and Climate Sensitivity

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# Anthropogenic Global Radiative Forcing of Climate

Radiative forcing of climate between 1750 and 2011

Forcing agent



# Climate Sensitivity-All about Feedbacks

$$\Delta T = \lambda \Delta F$$

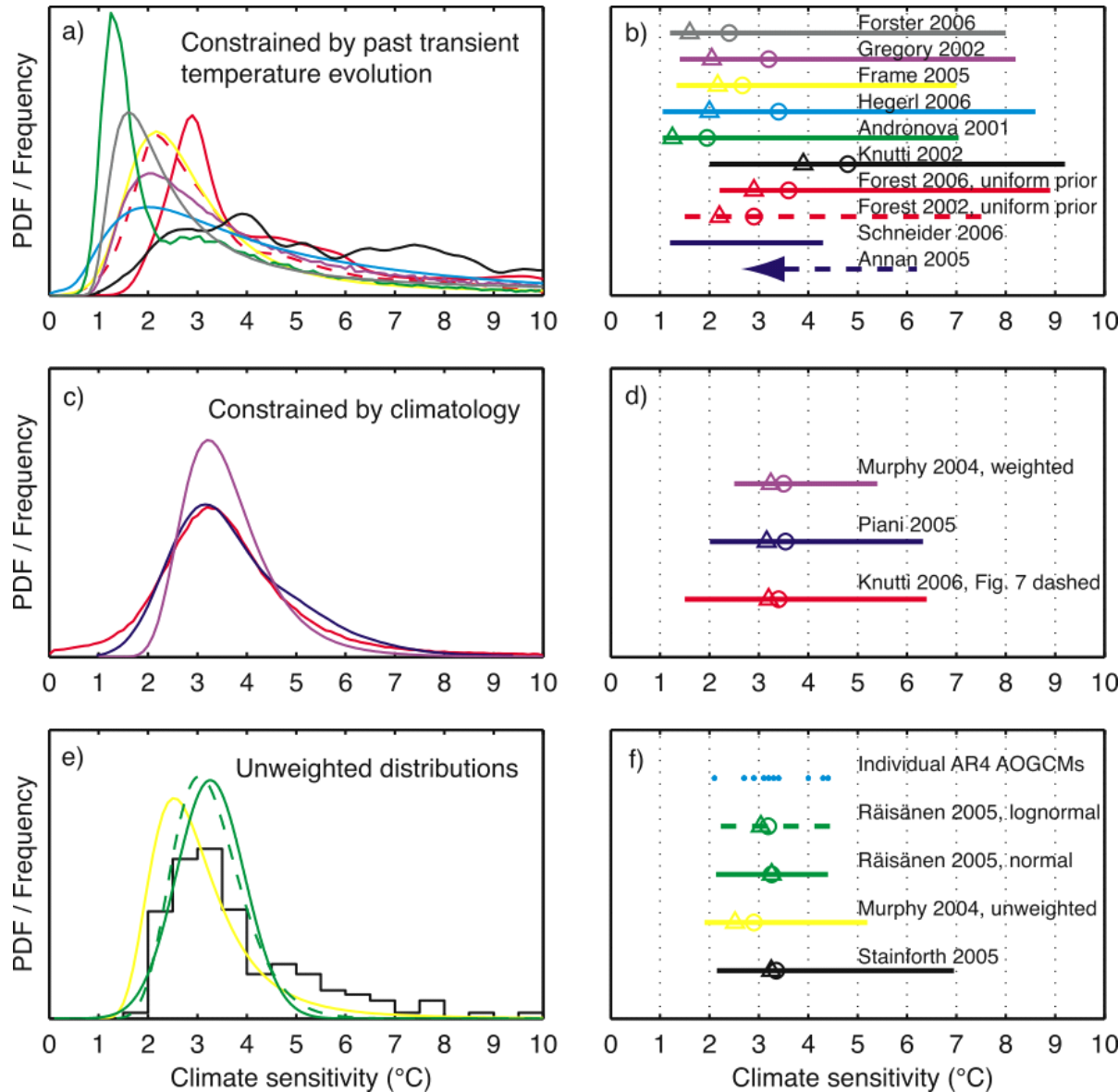
$\lambda$  is the *climate sensitivity parameter*

→ *units: K “per” W/m<sup>2</sup>*

→ **amount of climate change for a forcing**

→  **$\lambda$  determined by feedbacks!**

# Estimates of Climate Sensitivity



**T change for a  $4 \text{ W/m}^2$  forcing (i.e. “double  $\text{CO}_2$ ”)**

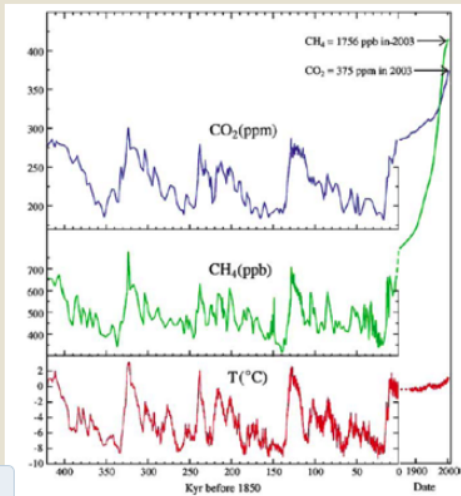


**Most probable  $\lambda \sim 0.75 \text{ K}/(\text{W/m}^2)$**

# Poll Question

**W** Globally averaged solar insolation varies by 0.2% every 100Kyr, equivalent to a  $-0.5 \text{ W/m}^2$  forcing. From this info and the T record in the ice core, only, estimate a climate sensitivity parameter.

When poll is active, respond at [PollEv.com/joelathornto254](https://poll-ev.com/joelathornto254) Text **JOELATHORNTO254** to **22333** once to join



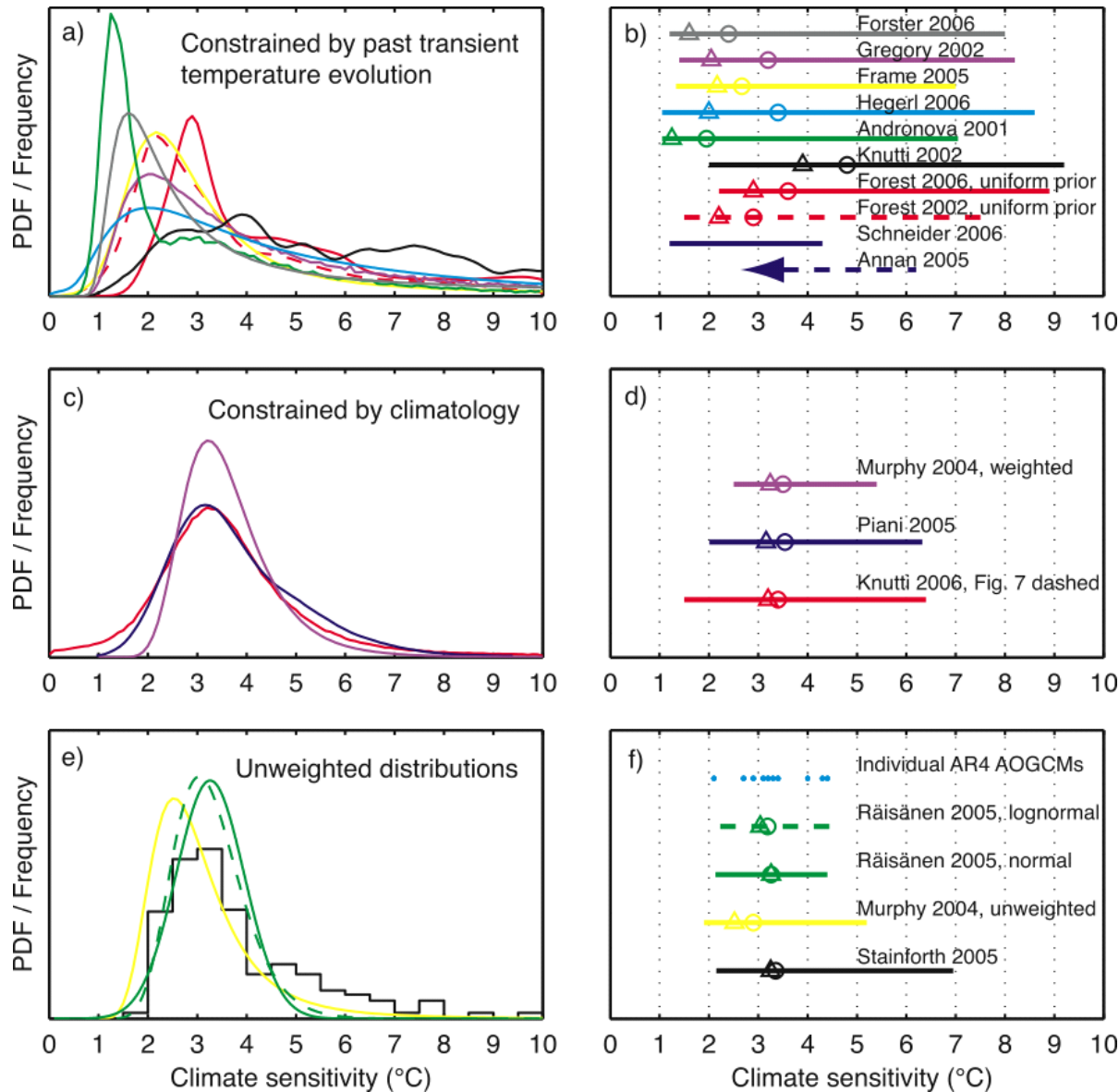
10 to 16 K/W/m<sup>2</sup>

3 to 5 K/W/m<sup>2</sup>

1 to 2 K/W/m<sup>2</sup>

Total Results: 0

# Estimates of Climate Sensitivity

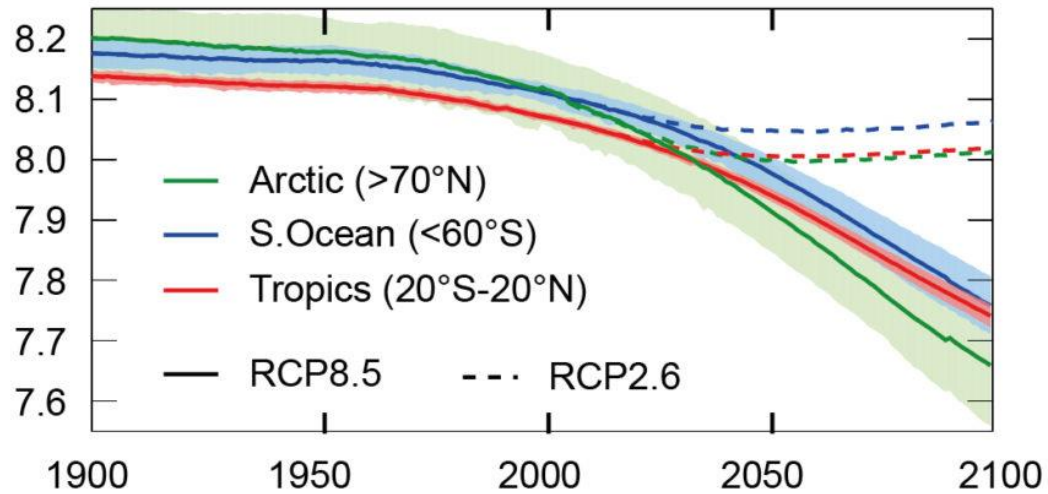


**T change for a  $4 \text{ W/m}^2$  forcing (i.e. “double  $\text{CO}_2$ ”)**



**Most probable  $\lambda \sim 0.75 \text{ to } 1 \text{ K}/(\text{W/m}^2)$**

a. Surface pH



b. Surface pH in 2090s (RCP8.5, changes from 1990s)

