

Kaya Identity Model: Predicting Future Emissions

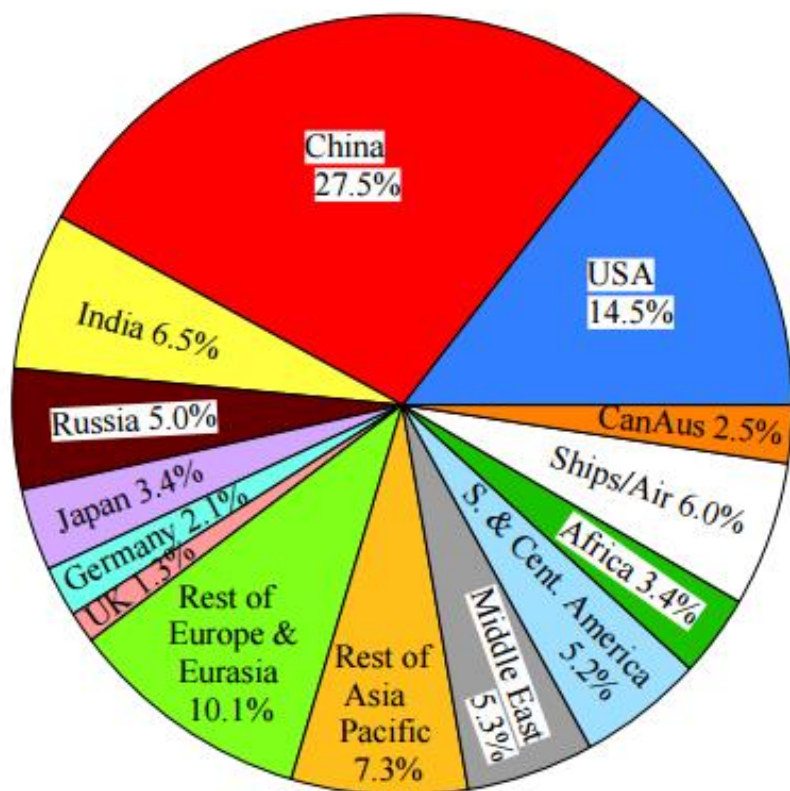
kaya identity model

Calculate Your Carbon Footprint

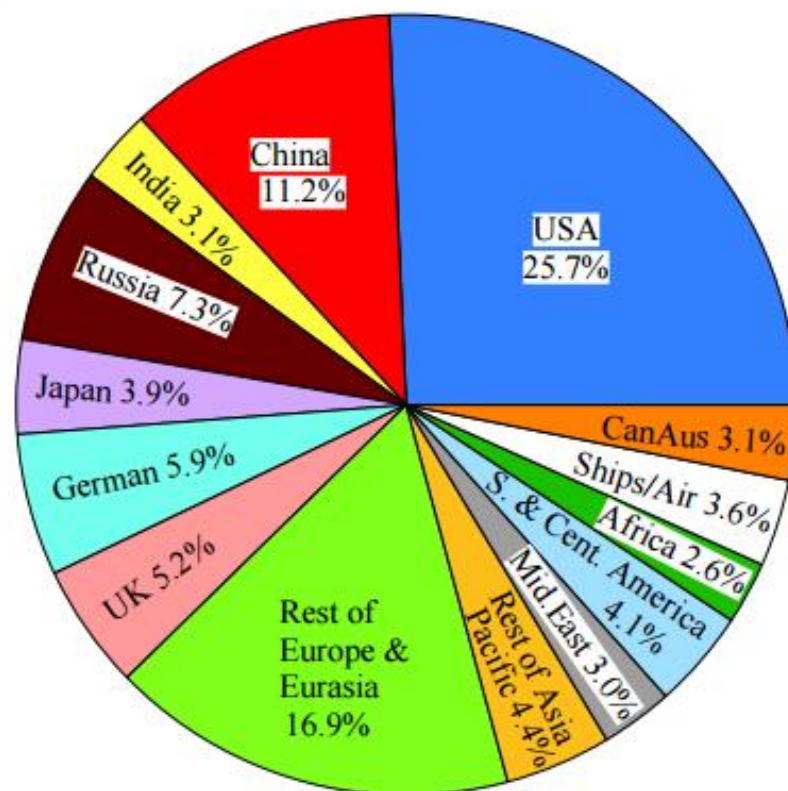
[Nature Conservancy Carbon Footprint Calculator](#)

Current and Cumulative Emissions by Country

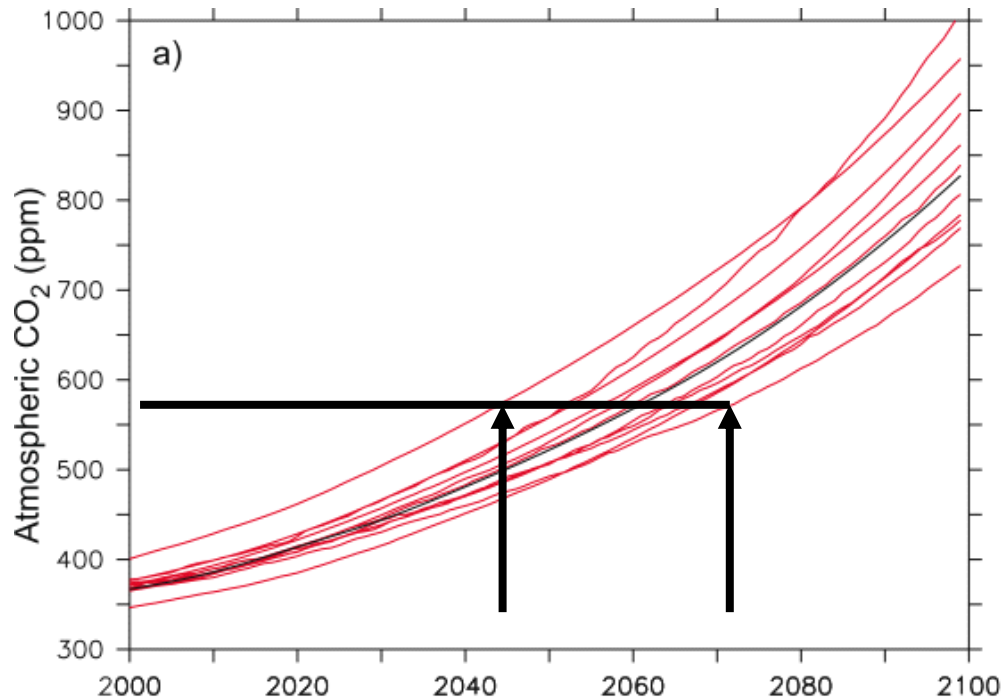
(a) 2013 Annual Emissions (9.9 GtC/yr)



(b) 1751–2013 Cumulative Emis. (394 GtC)



Future Atmospheric CO₂



One anthropogenic emission scenario in many different IPCC models

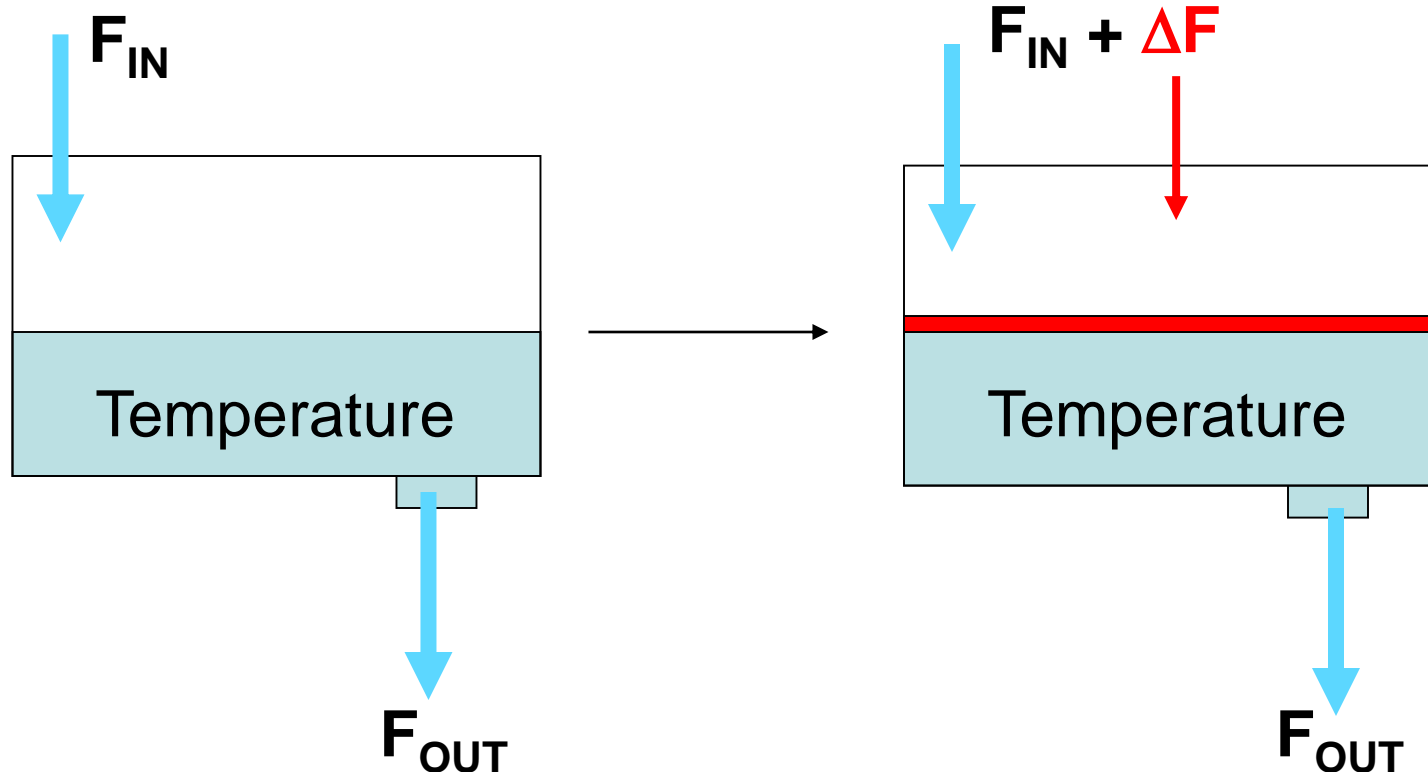
Range of model predictions suggest double pre-industrial (2 x 280 ppm) by mid-century

This Week (and next): Climate Forcings

- **Natural**
 - **Orbital (long-term)**
 - **Solar (short-term)**
 - **Volcanic (short-term)**
- **Anthropogenic**
 - **Greenhouse effect (via Carbon Cycle)**
 - **Albedo (via Aerosol Particles)**

Climate Forcings

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



Radiative Forcing

Climate Sensitivity-All about Feedbacks

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

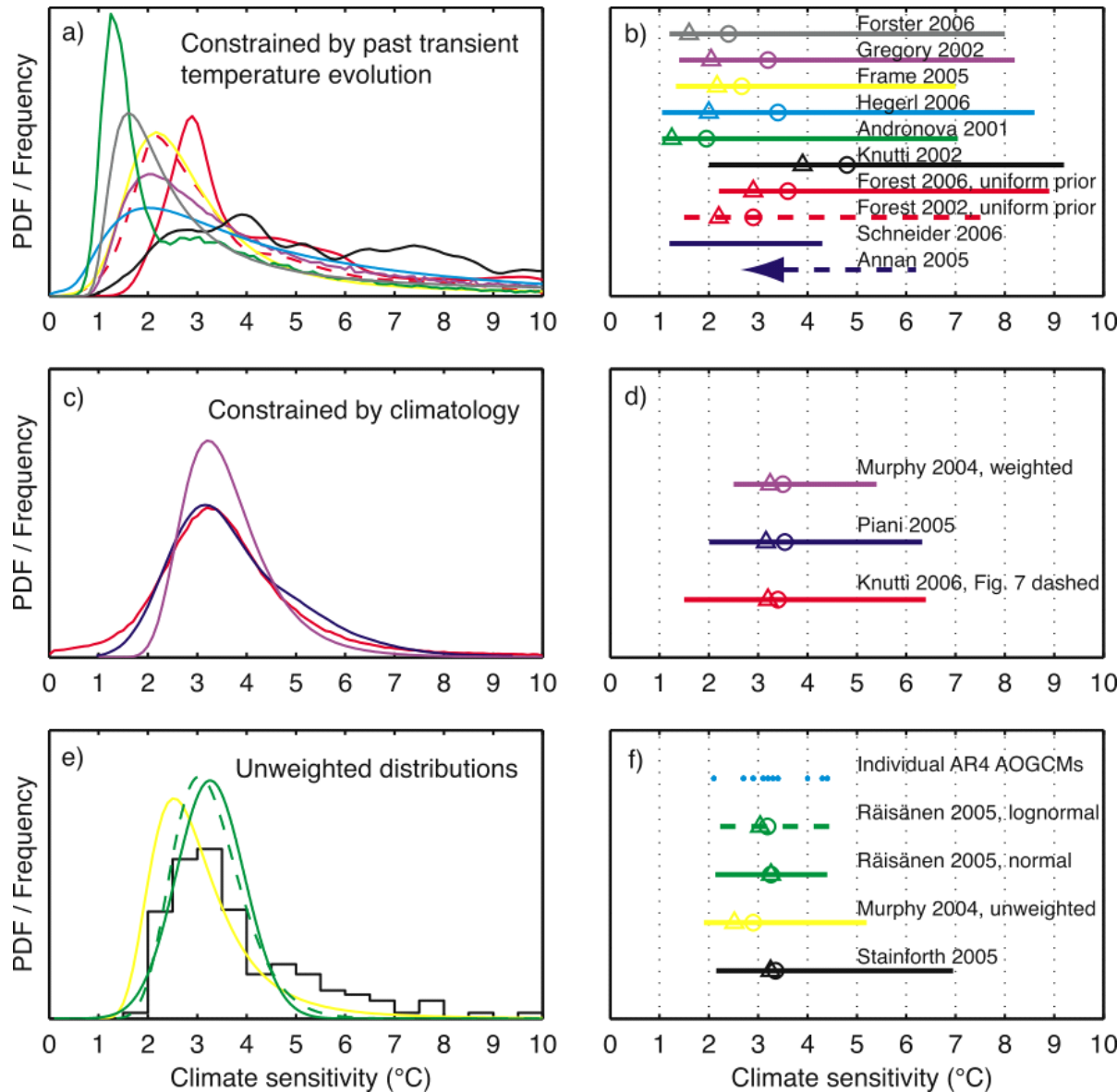
λ is the *climate sensitivity parameter*

→ *units: K “per” W/m²*

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

→ **λ determined by feedbacks!**

Estimates of Climate Sensitivity

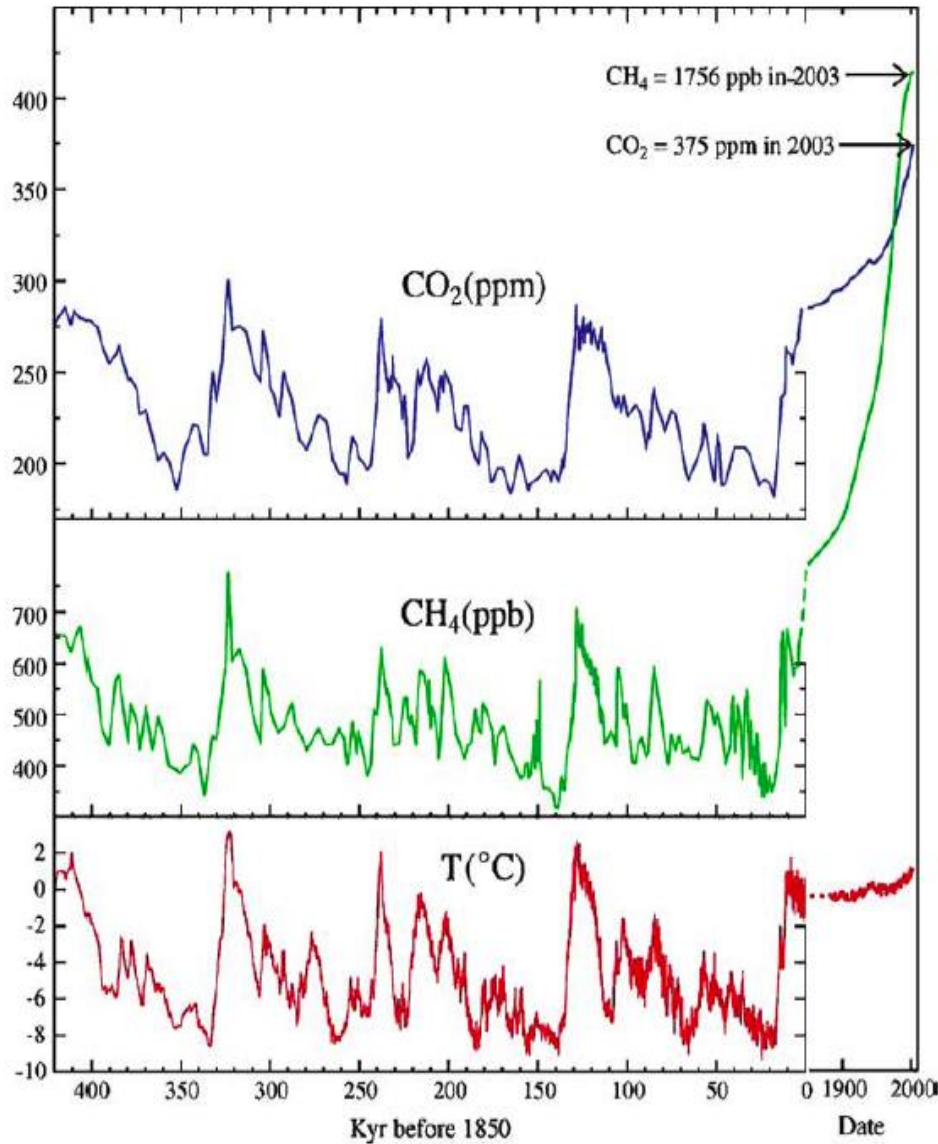


T change for a 4 W/m^2 forcing (i.e. “double CO_2 ”)



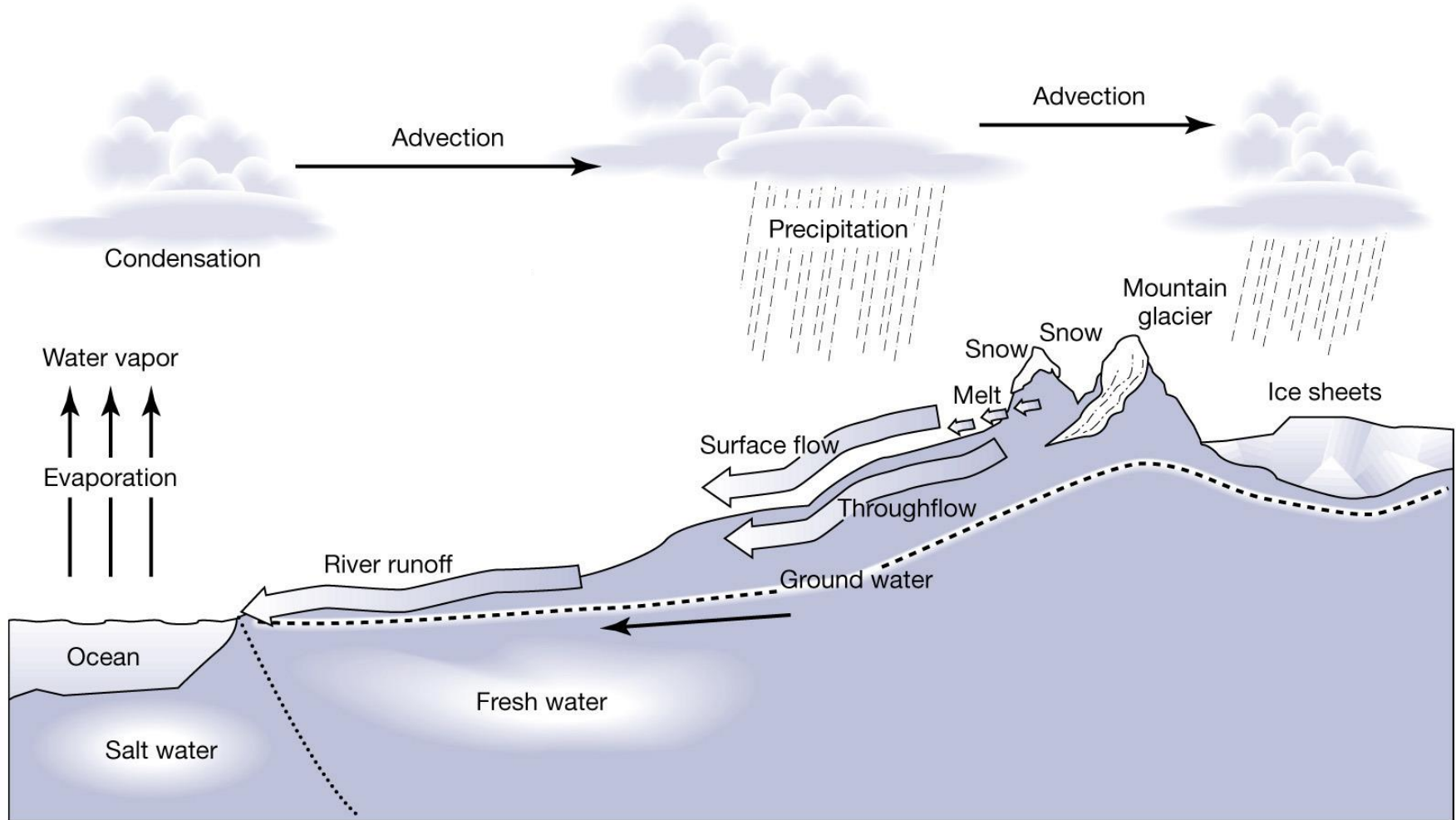
Most probable $\lambda \sim 0.75 \text{ K}/(\text{W/m}^2)$

Pleistocene Ice Ages



Large (but slow)
natural changes in
global hydrologic cycle

Water Cycle – During Glacial-Interglacial Periods



**“Ice ages” – Net transfer of water from ocean to land-based ice sheets
→ Sea levels decrease**

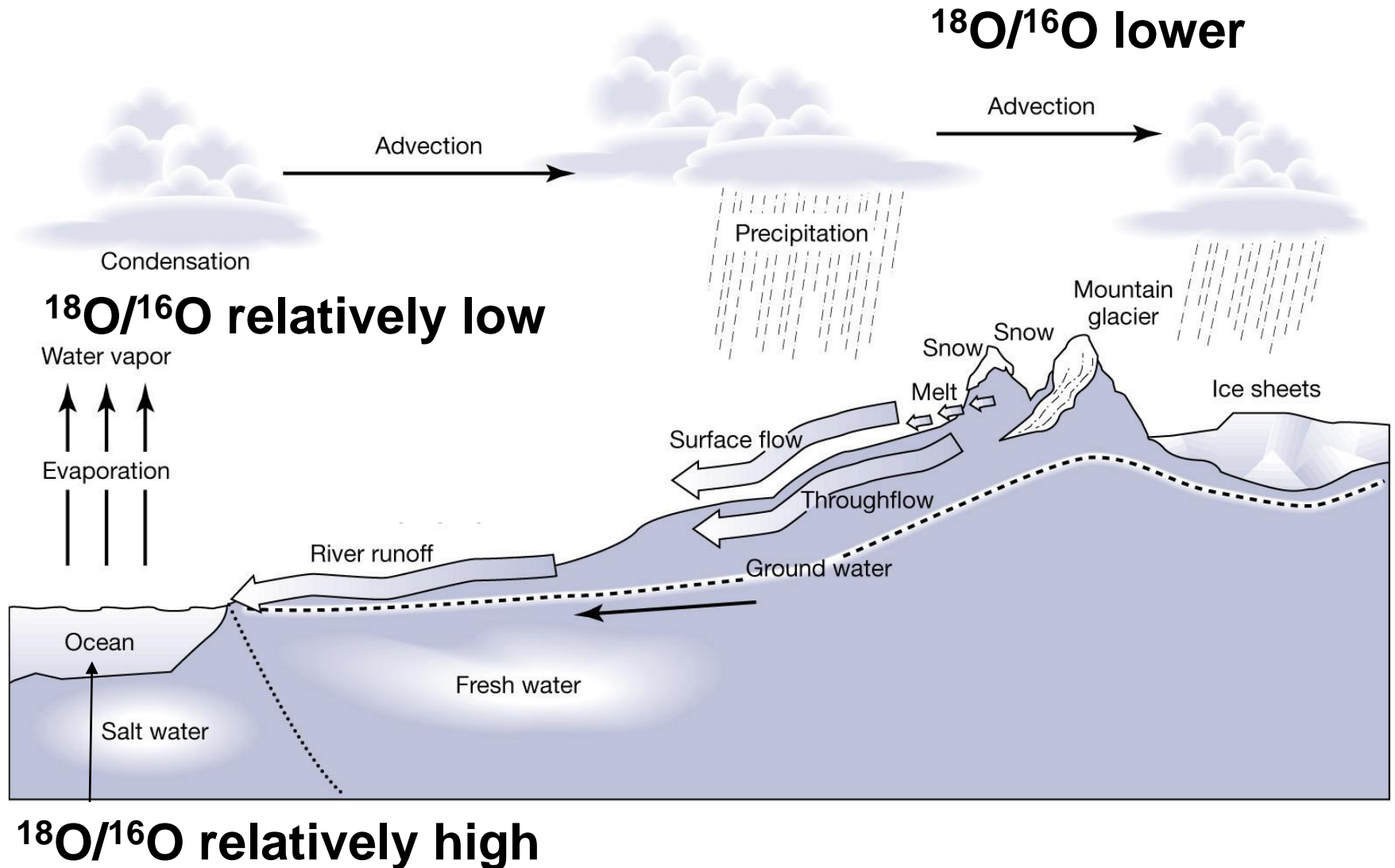
Detecting Change With Proxies

Another property/qty that is a ***function*** of (i.e. depends upon) property of interest.

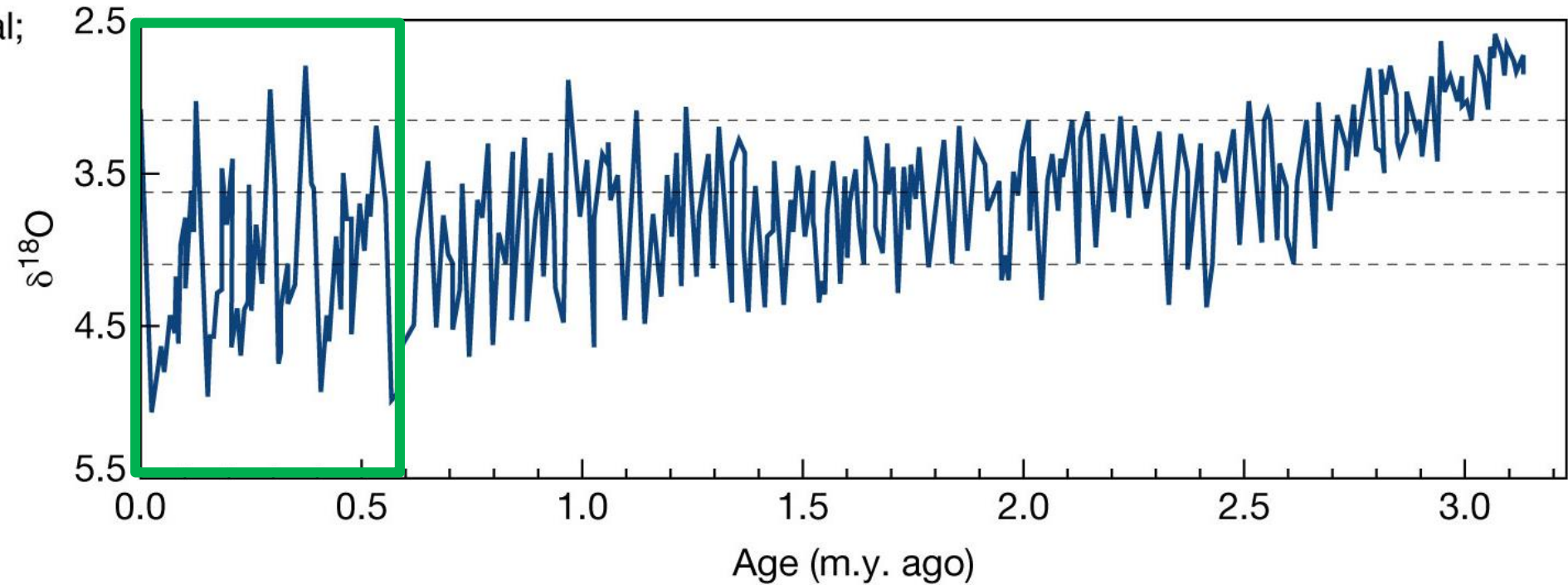
Think *approximate*

The measured property is a **PROXY** for the one of interest.

Water Cycle – Water Isotope Proxy



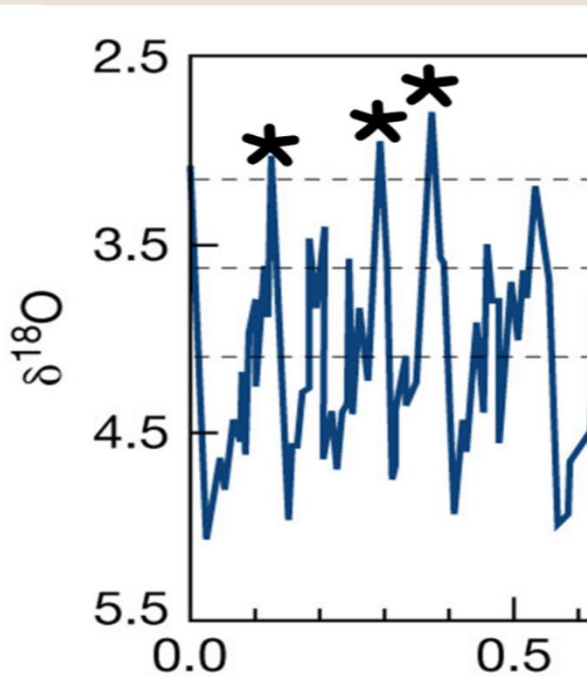
^{18}O Ratios in Sediment and Ice Core



W

The times in the sediment record indicated by the '*' correspond to

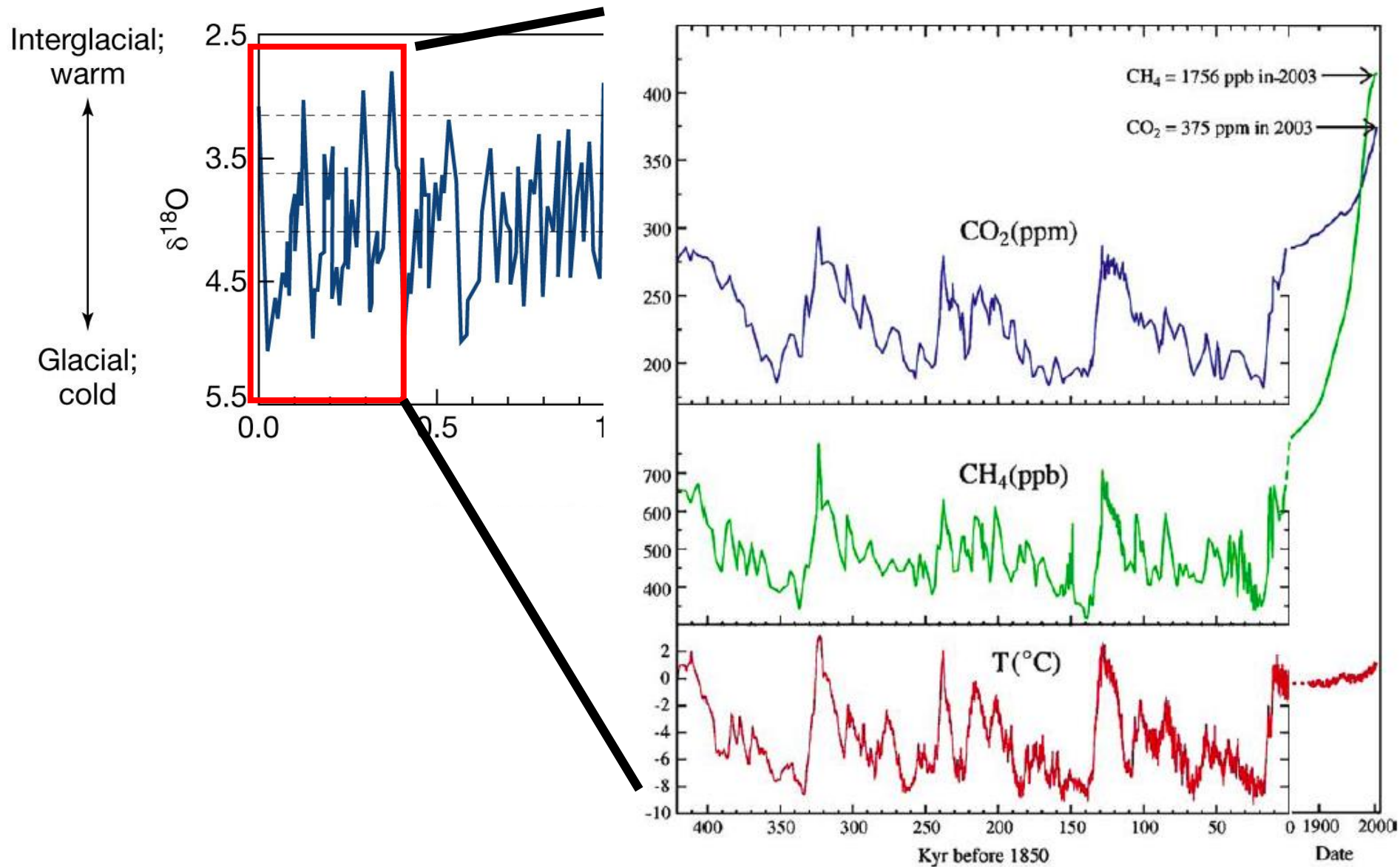
 **Poll locked.** Responses not accepted.



Net glaciation (ice sheet growth)

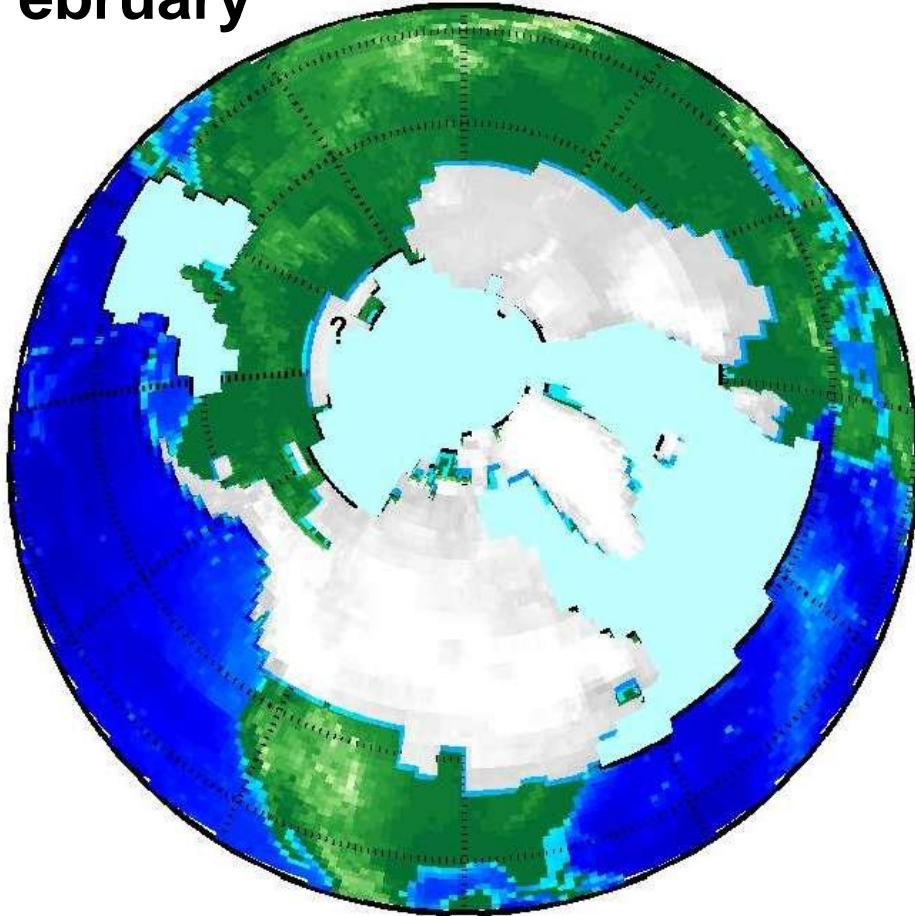
Net deglaciation (ice sheet retreat)

^{18}O Ratios in Sediment and Ice Core



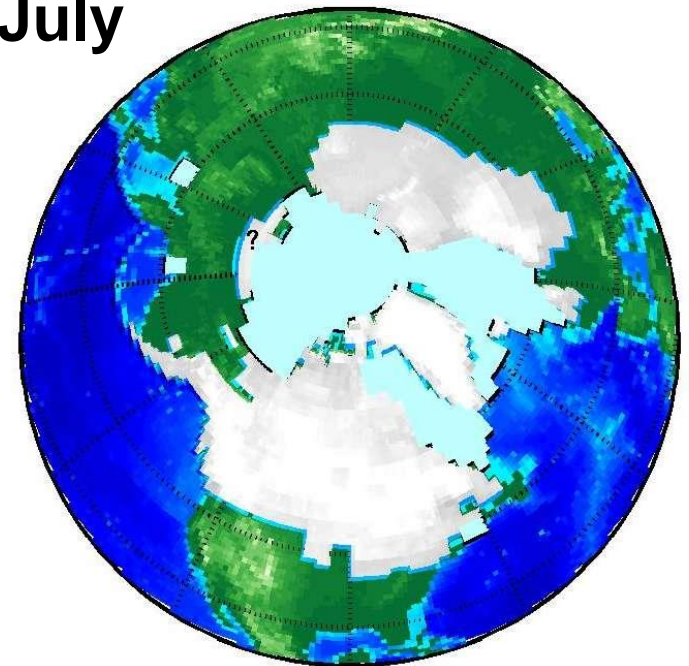
Pleistocene Glaciations

February



**Sea Levels lower by
100 m (300 ft)!**

July



Reconstruction of land and sea ice
21,000 years ago (last glacial maximum)

Records of NH Glaciations

Geological Records: glacial deposits, drop stones, scarring



Cordilleran Ice Sheet

Lake Missoula

Spokane Floods (from Lake Missoula)

One of “7 Wonders of WA”: Channeled Scablands



MARY WARDLEY, NG STAFF
SOURCES: USGS; ATLAS OF OREGON

<https://news.nationalgeographic.com/2017/03/channeled-scablands/>

One of “7 Wonders of WA”: Channeled Scablands



Drop Stone in Wedgewood Neighborhood...



The "Wedgewood Erratic" was stranded when the ice retreated. Today this massive rock sits north of the University of Washington campus - at the corner of NE 72nd Street and 28th Ave NE.

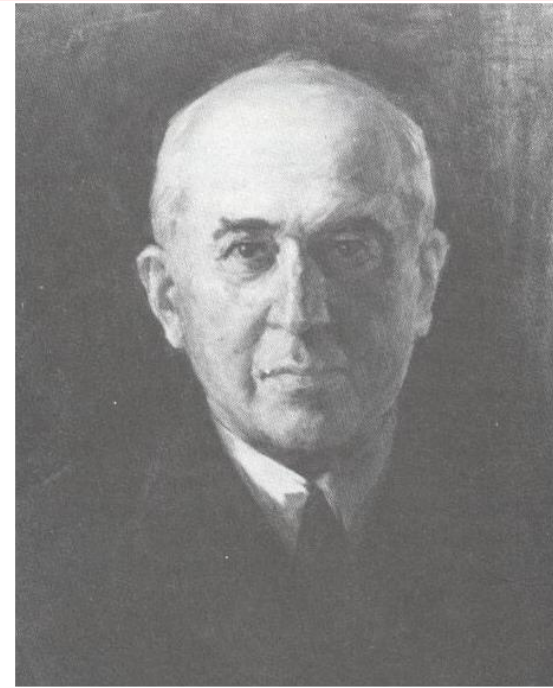
HUGEfloods.com

Milankovitch—Before sediment/ice cores

Predicts glacial and interglacial transitions based on variations in Earth's orbit

His hypothesis suggested *many* such transitions in ~ 1 million yrs (he was right)

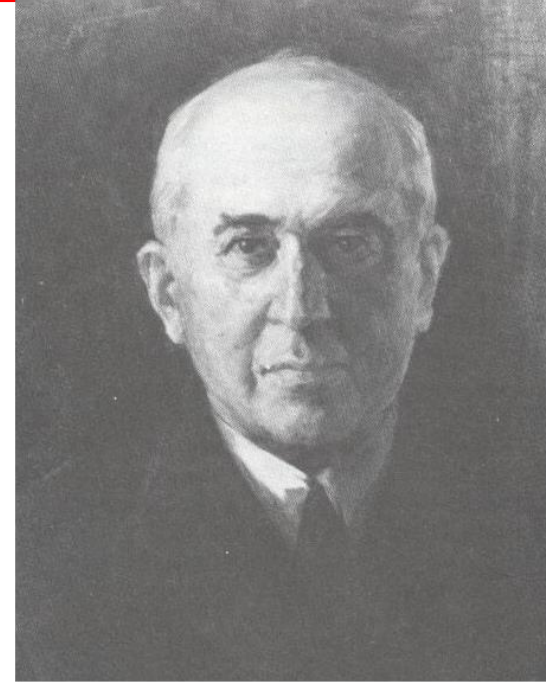
—at the time, no observable records show that many, so his work widely criticized



Milutin Milankovitch

Milankovitch Continued

**While lacking patience for critics,
he did not lack confidence**



Milutin Milankovitch

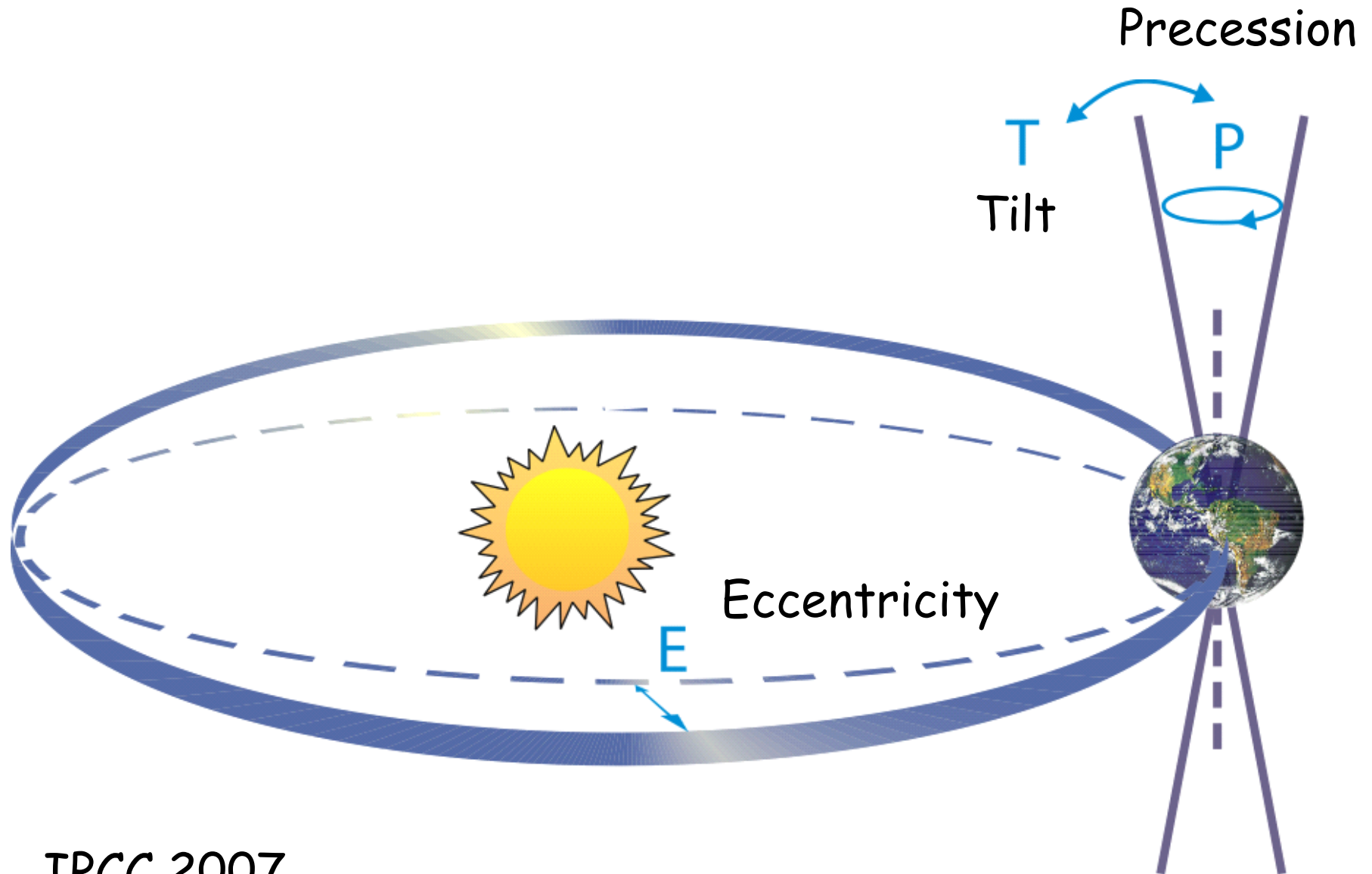
“I do not consider it my duty to give an elementary education to the ignorant, and I have also never tried to force others to use my theory, with which no one could find fault.”

Orbital Forcings – Milankovitch Cycles

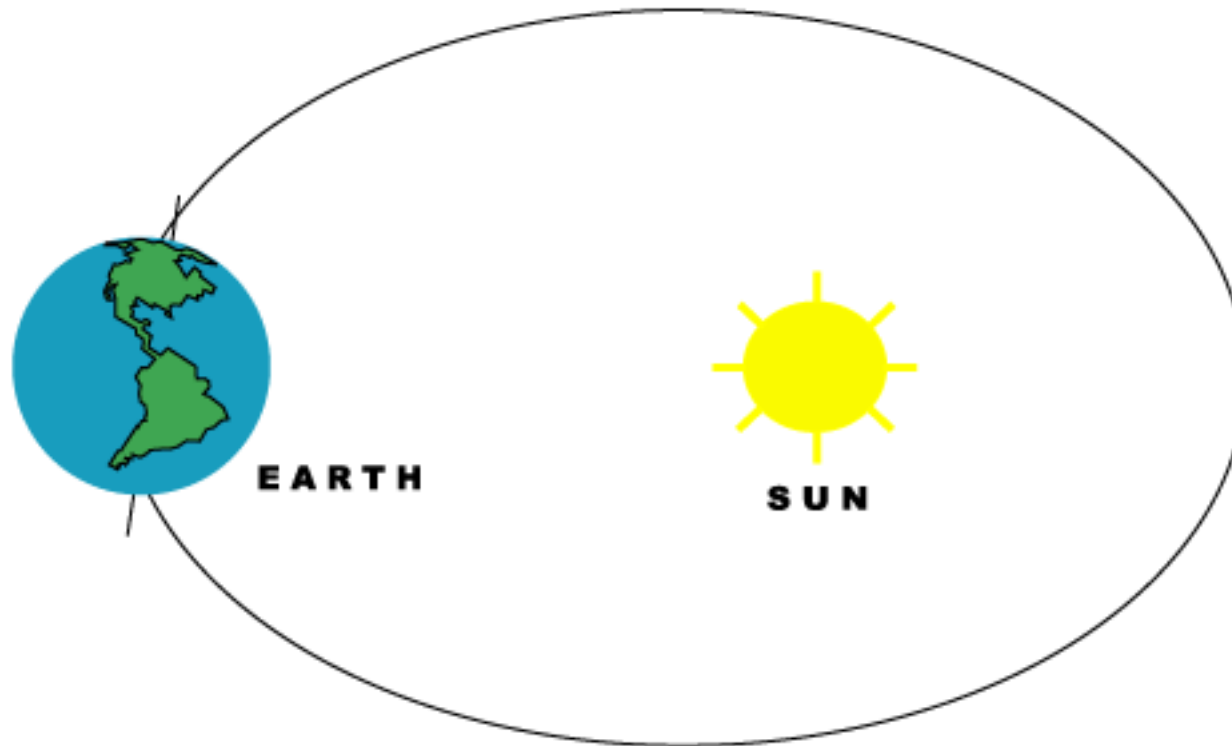
- **Small variations in Earth's orbital parameters affect seasonal distribution of solar insolation**
- **Three oscillations (eccentricity, obliquity, precession) occur “in parallel”, each with a characteristic frequency**
- **Net effect: glacial – interglacial “heartbeats” of Pleistocene (2.5 Ma – 10Kyr before present)**

Orbital Forcings

Orbital Forcing Summary



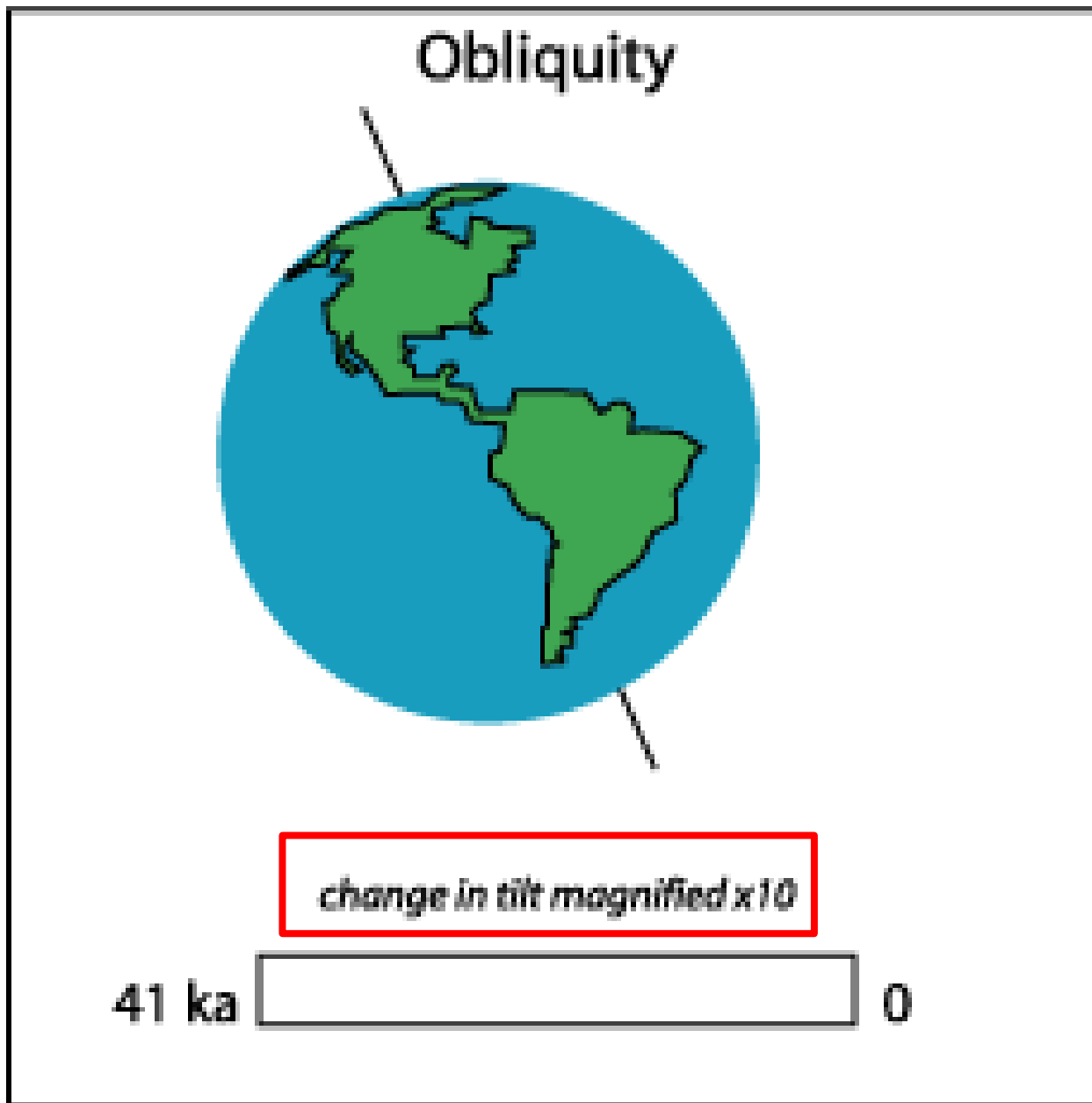
Eccentricity: More to Less Circular



100 90 80 70 60 50 40 30 20 10 0

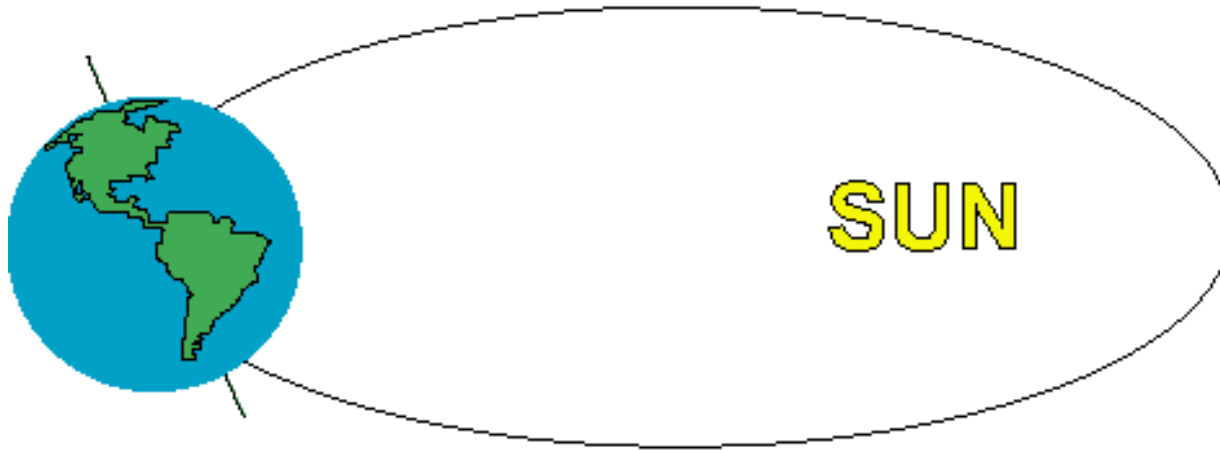
Time * 1000 years ago

Obliquity: More or Less Seasonality

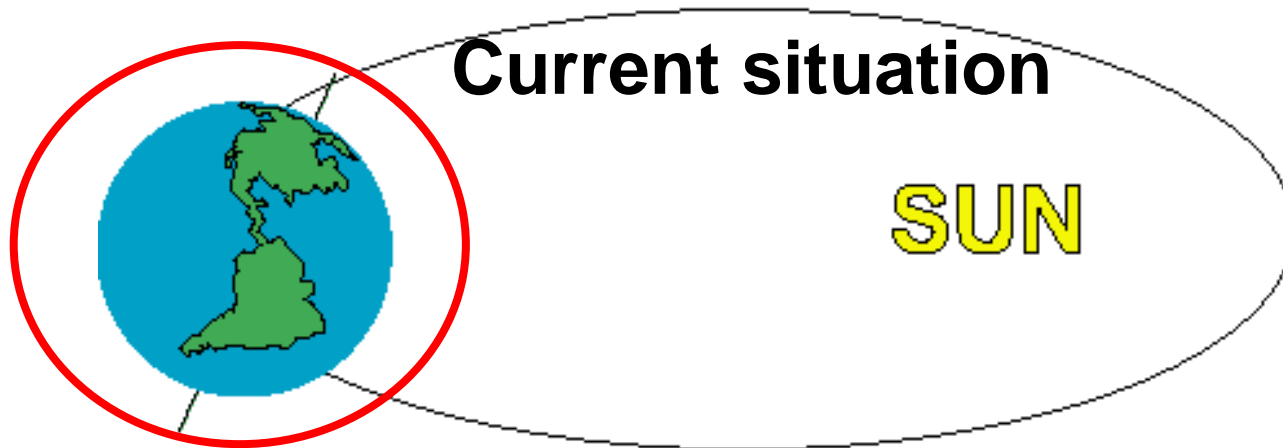


Must Consider Precession *and* Eccentricity Cycles

Precession of the Equinoxes (19 and 23 k.y.)



Southern Hemisphere tilted toward the Sun at aphelion



Northern Hemisphere tilted toward the Sun at aphelion

W

Currently NH summer takes place at aphelion, in about 11,000 years, NH summer will occur at perihelion. At this time, SH seasonality will be



Respond at PollEv.com/thornton211



Text **THORNTON211** to **22333** once to join, then **1** or **2**

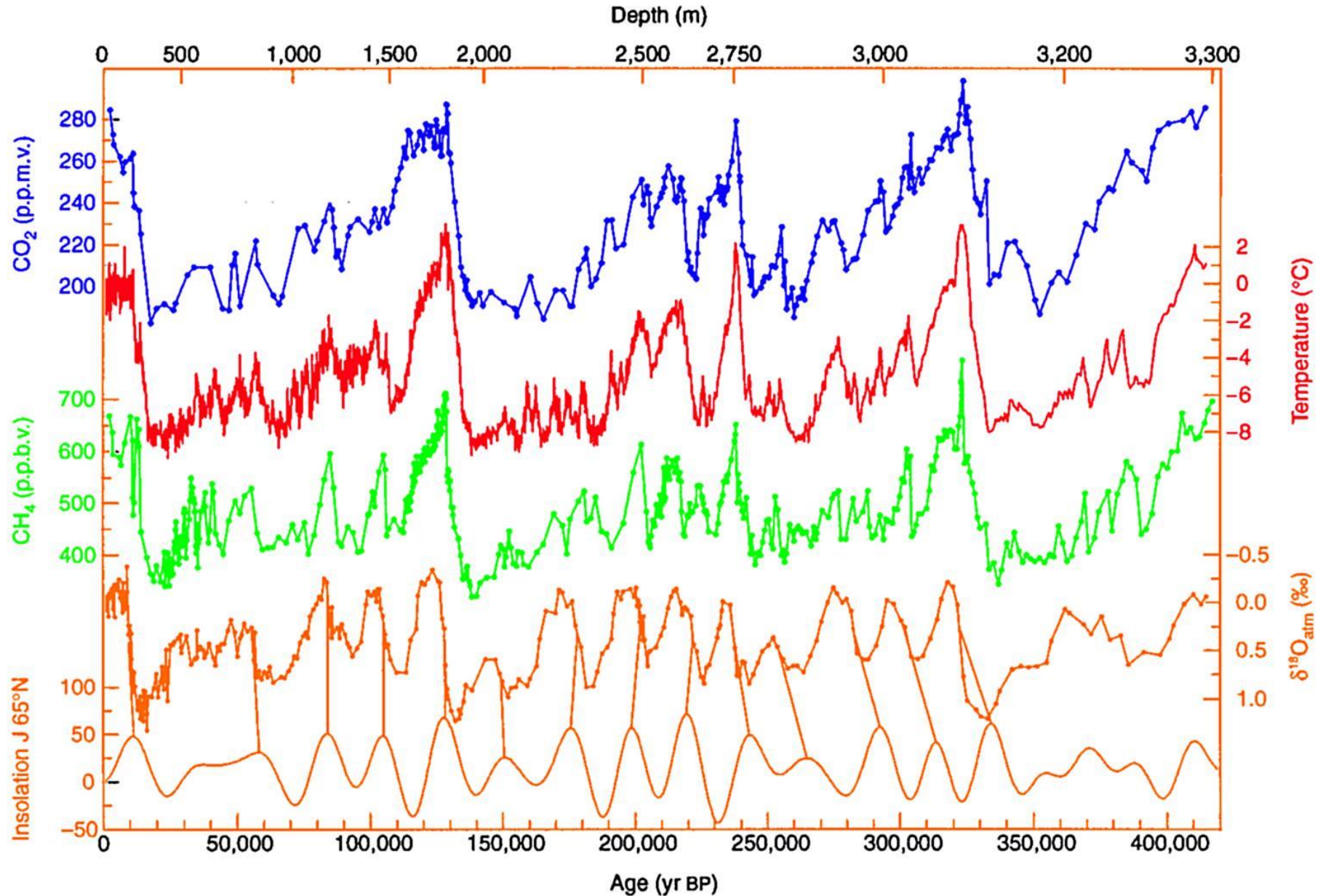
Stronger than it is now

1

Weaker than it is now

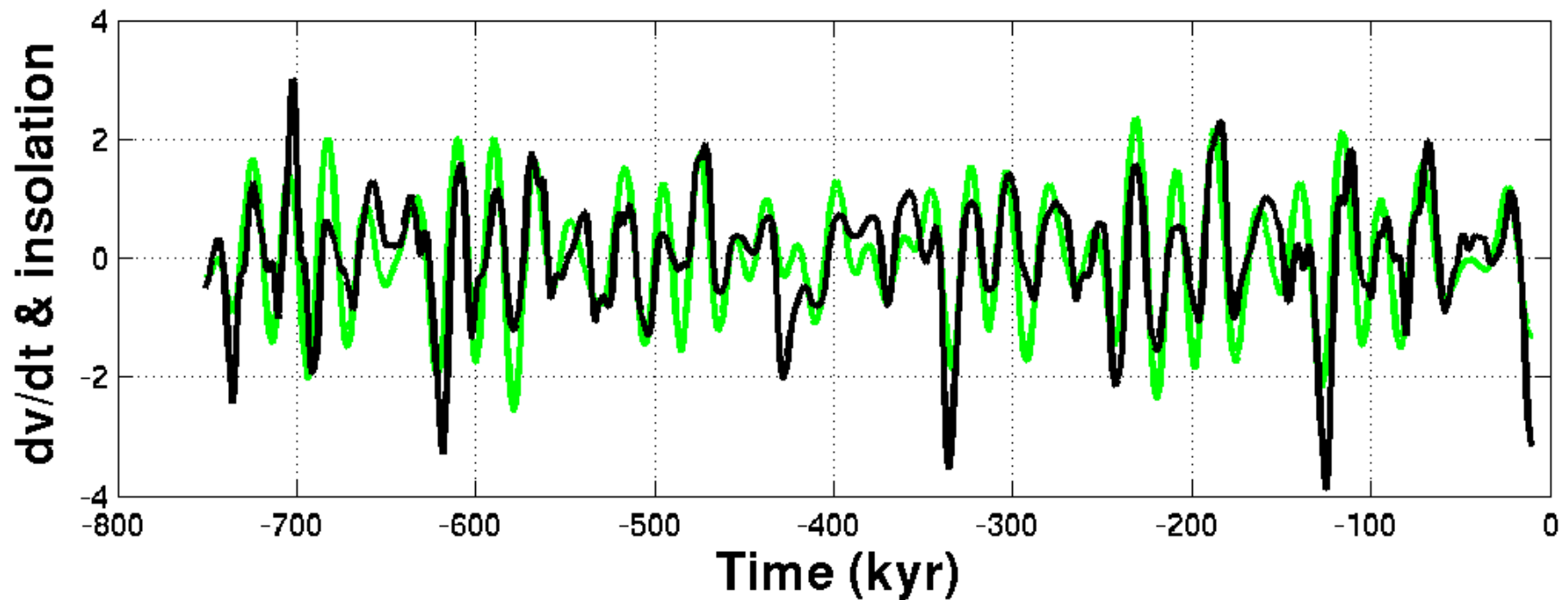
2

Solar Insolation at 65N and Glaciation



UW Research – Gerard Roe (ESS)

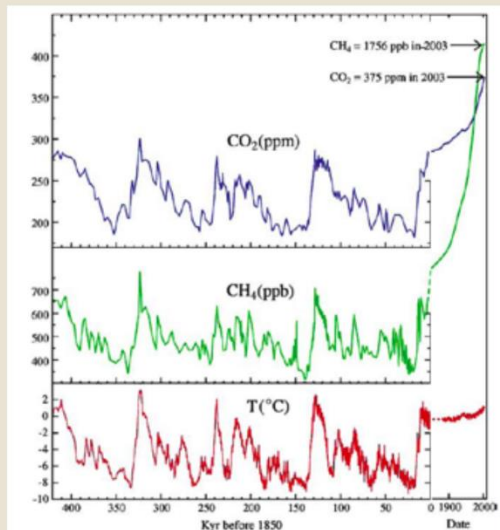
Rate of change of ice volume and NH solar insolation



W

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

 **Poll locked.** Responses not accepted.



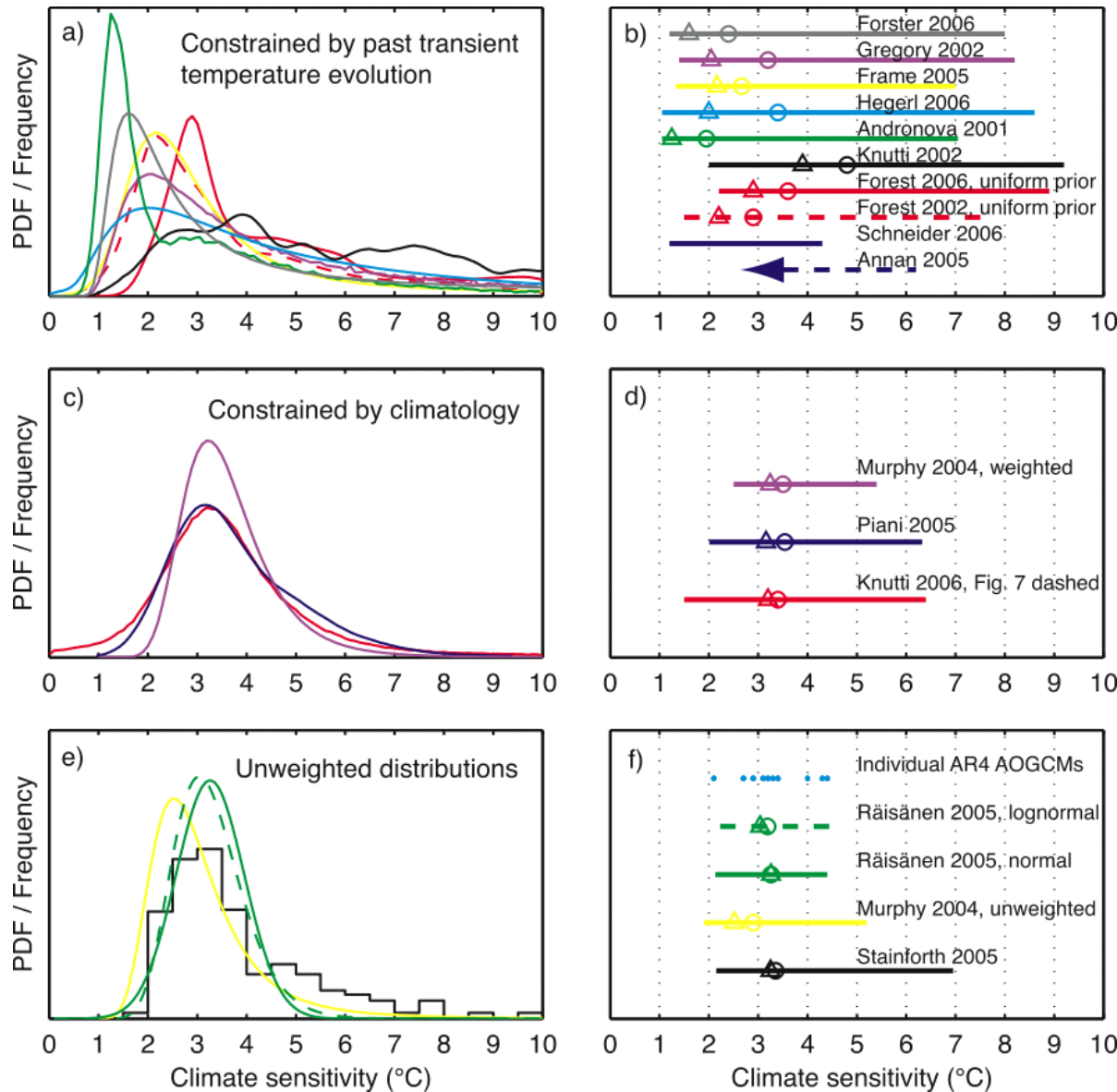
10 to 16 K/W/m²

3 to 5 K/W/m²

1 to 2 K/W/m²

Total Results: 0

Estimates of Climate Sensitivity



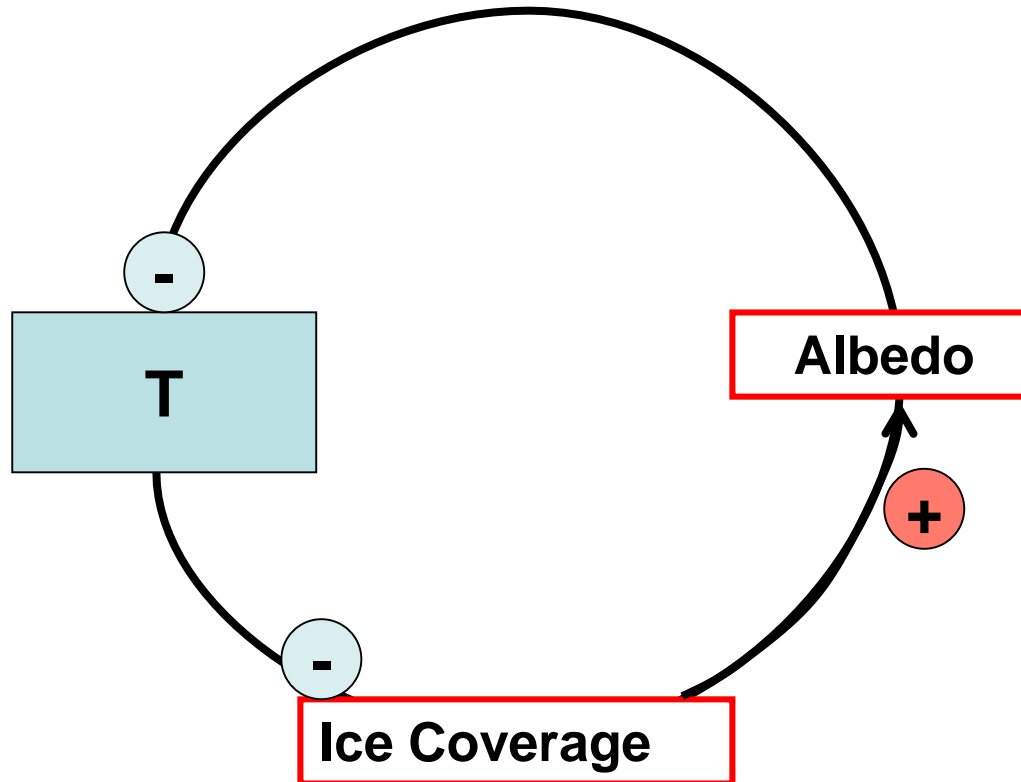
T change for a 4 W/m^2 forcing (i.e. “double CO_2 ”)



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

A Crucial Feedback: Ice Albedo Feedback

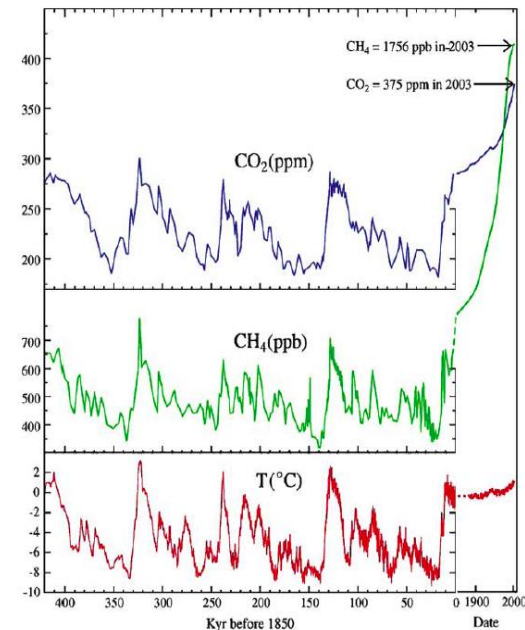
Solar insolation in NH summer appears to be key for *maintaining glaciation*. Ice sensitive to melting!



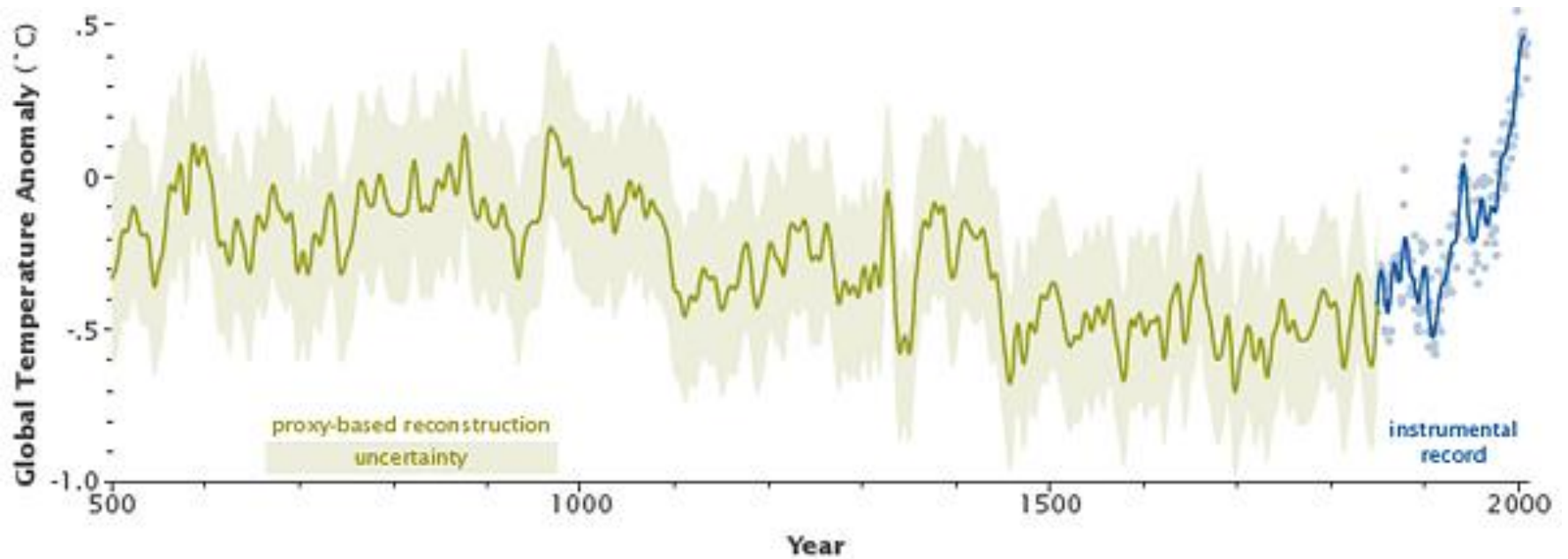
Overall positive (destabilizing) feedback

What did the Pleistocene Ice Ages teach us?

- Changes in Earth's orbit are a natural (continuous) forcing on climate
 - timescales are slow (50 – 100K/yr) and the magnitude of the forcing is small!
- A small forcing can translate into a large climate change via positive feedbacks, examples for ice ages:
 - Ice-albedo feedback
 - Marine biological pump (atmospheric CO₂ decreases)
 - Temperature-Water Vapor-GHE
- Same positive feedbacks exist in present day, and will contribute to global warming



Recent Millenial Temperature Record



Natural Short-term Forcings

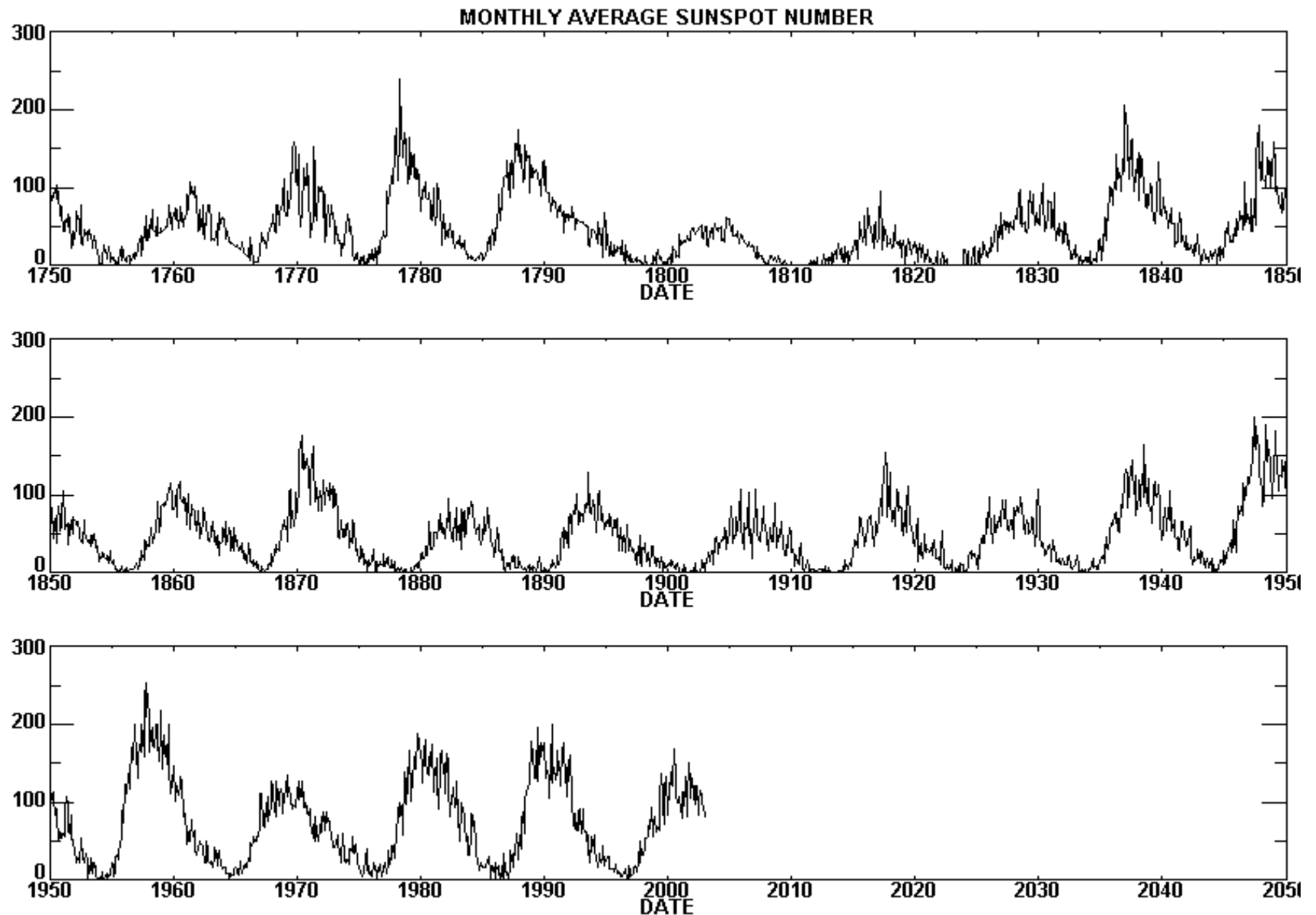
- “It is all caused by natural variations”
- 11 year Solar Cycle (Sunspot Cycle)
- Volcanic (Aerosol) Forcing

Sunspots – Cyclic Changes in Solar Output (S_0 Forcing)



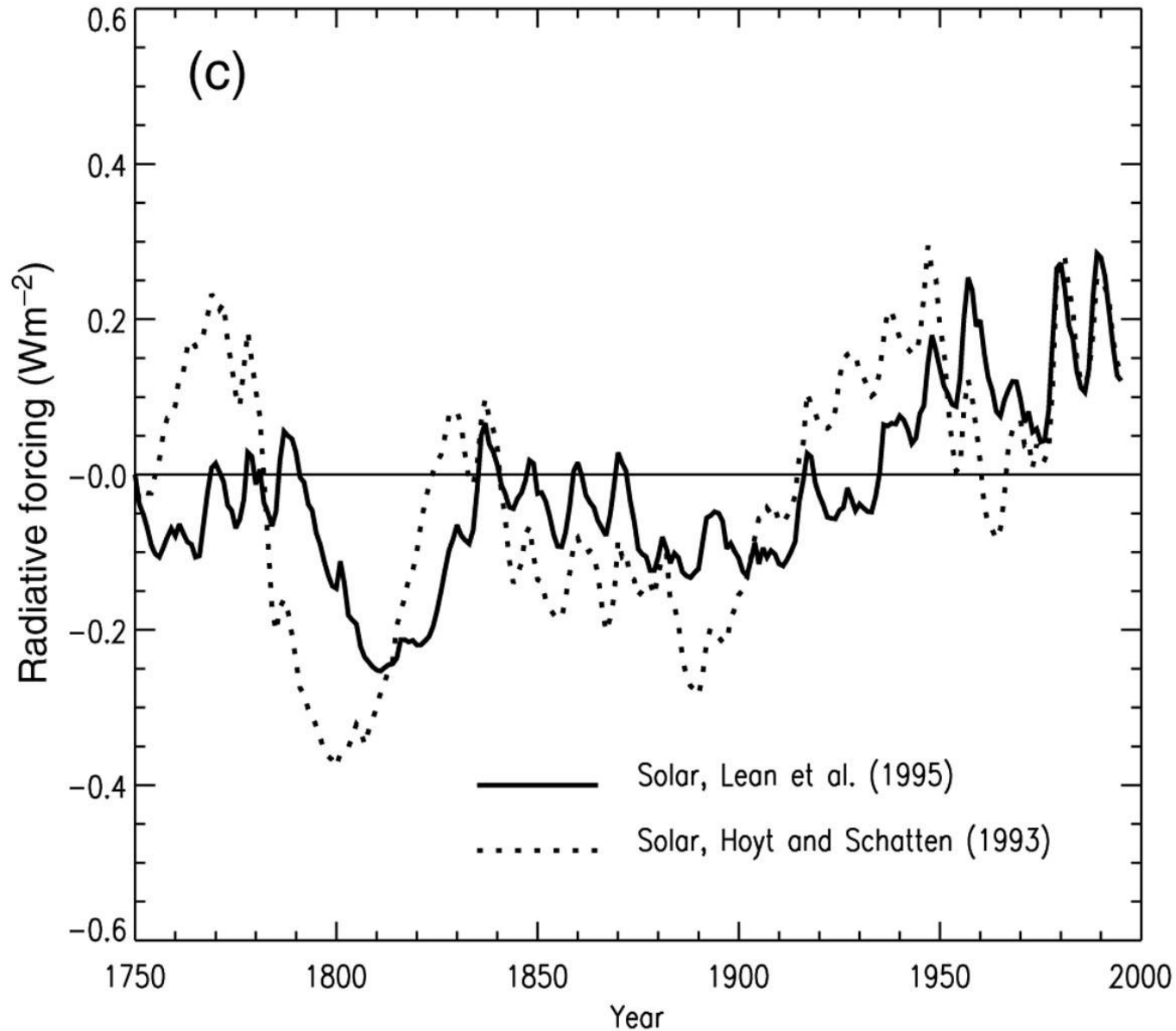
Sunspot drawings by Christoph Scheiner from his book *Rosa Ursina*.

~11 year Sunspot Cycle



Solar (“Sunspot”) Cycle

Radiative Forcing by Solar Cycle



Poll Question

W

Earth's global average temperature has increased by about 1 K since 1900. The solar cycle forcing has been about 0.3 W/m^2 since 1900. Assuming a climate sensitivity parameter of 1 K/W/m^2 , the solar forcing explains



When poll is active, respond at Pollev.com/joelathornto254



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

65-75% of the observed T increase

45-55% of the observed T increase

25-35% of the observed T increase

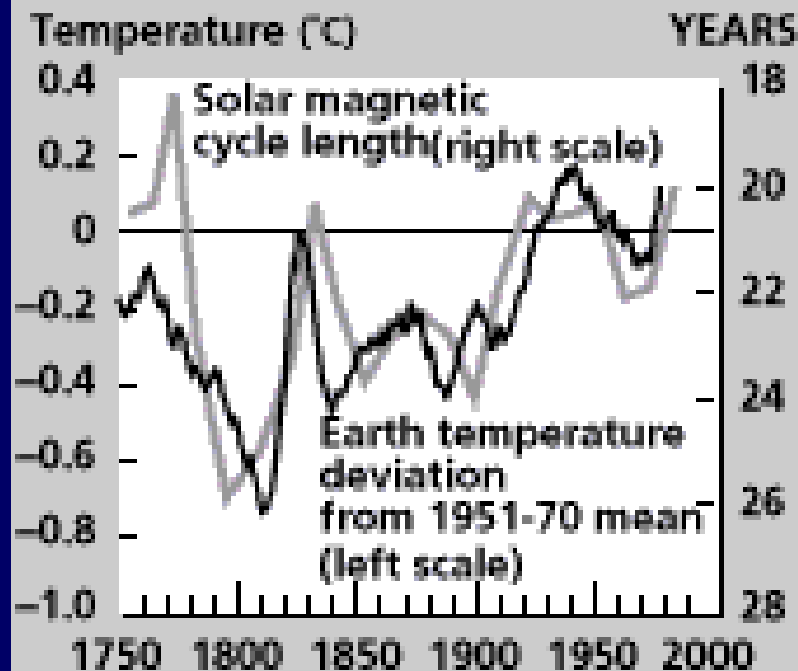


Total Results: 0

False Assertions: Sun – Global Warming

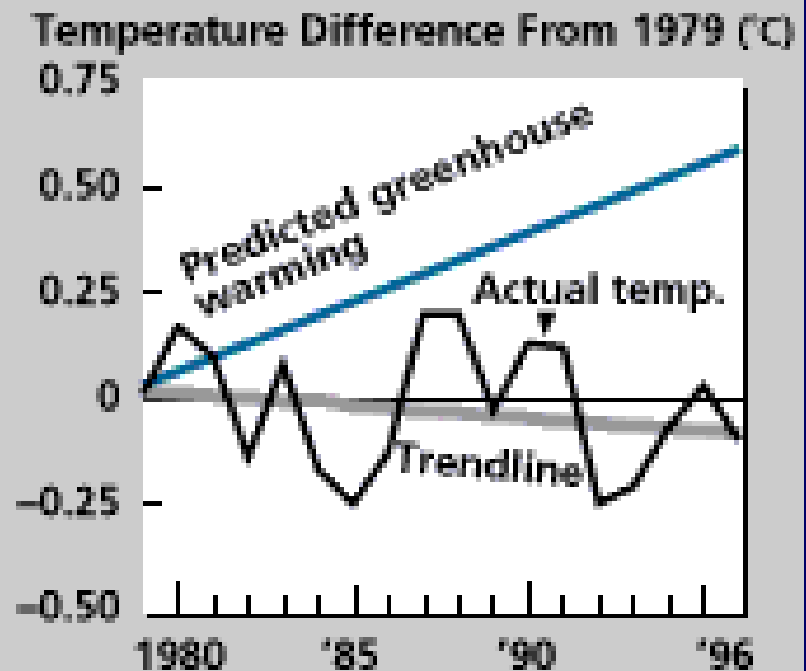
WHAT WARMS THE EARTH?

It's Solar Activity ...



Source: *Astrophysical Journal*

... Not Carbon Dioxide



Source: *Marshall Institute*

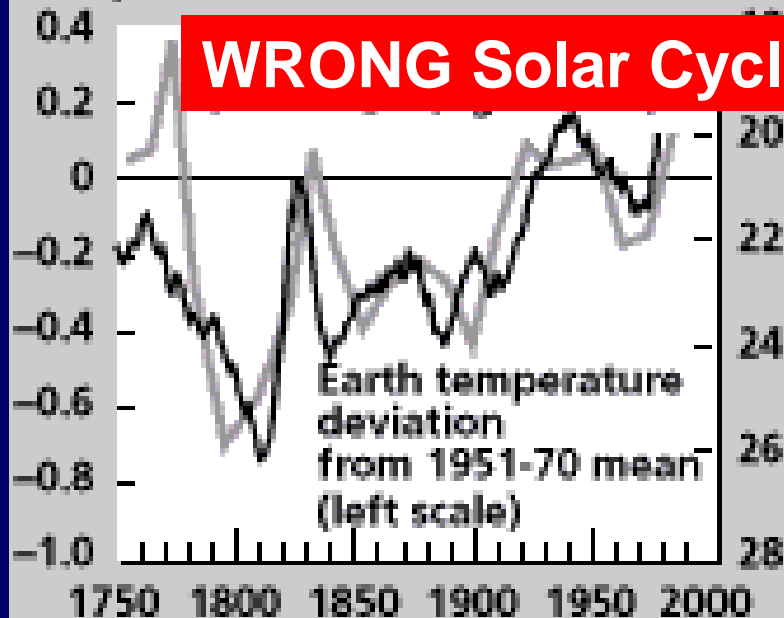
Originally from WSJ Article written by two chemists named Robinson

False Assertions: Sun – Global Warming

WHAT WARMS THE EARTH?

It's Solar Activity ...

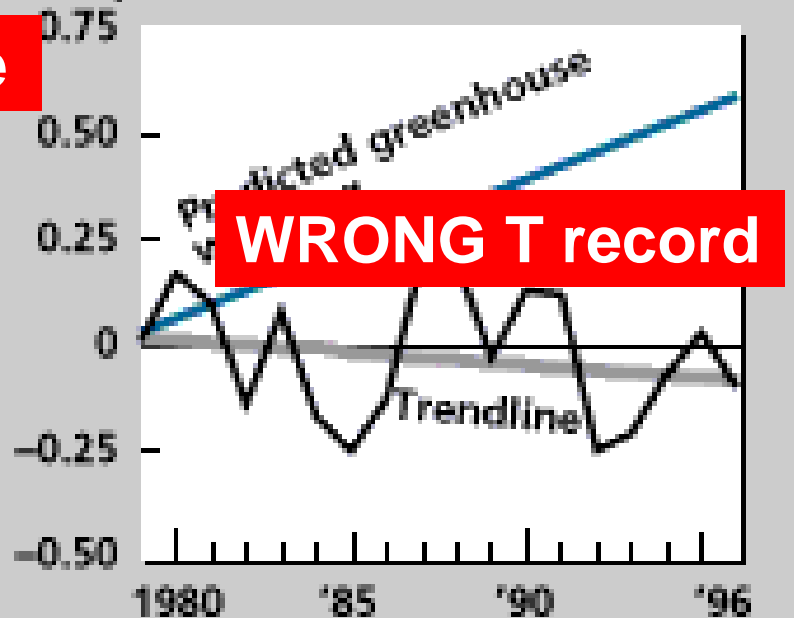
Temperature (°C)



Source: *Astrophysical Journal*

... Not Carbon Dioxide

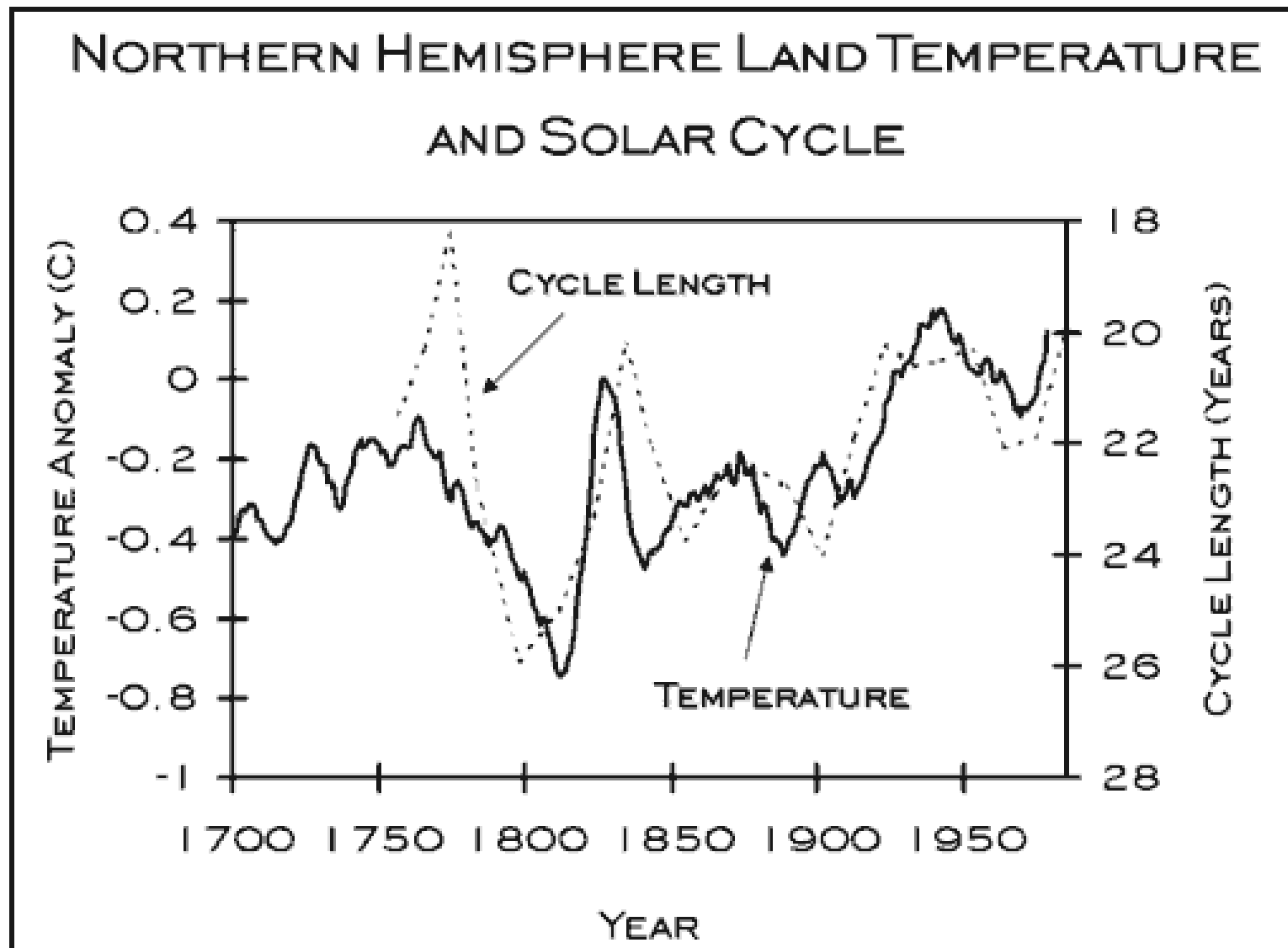
Temperature Difference From 1979 (°C)



Source: *Marshall Institute*

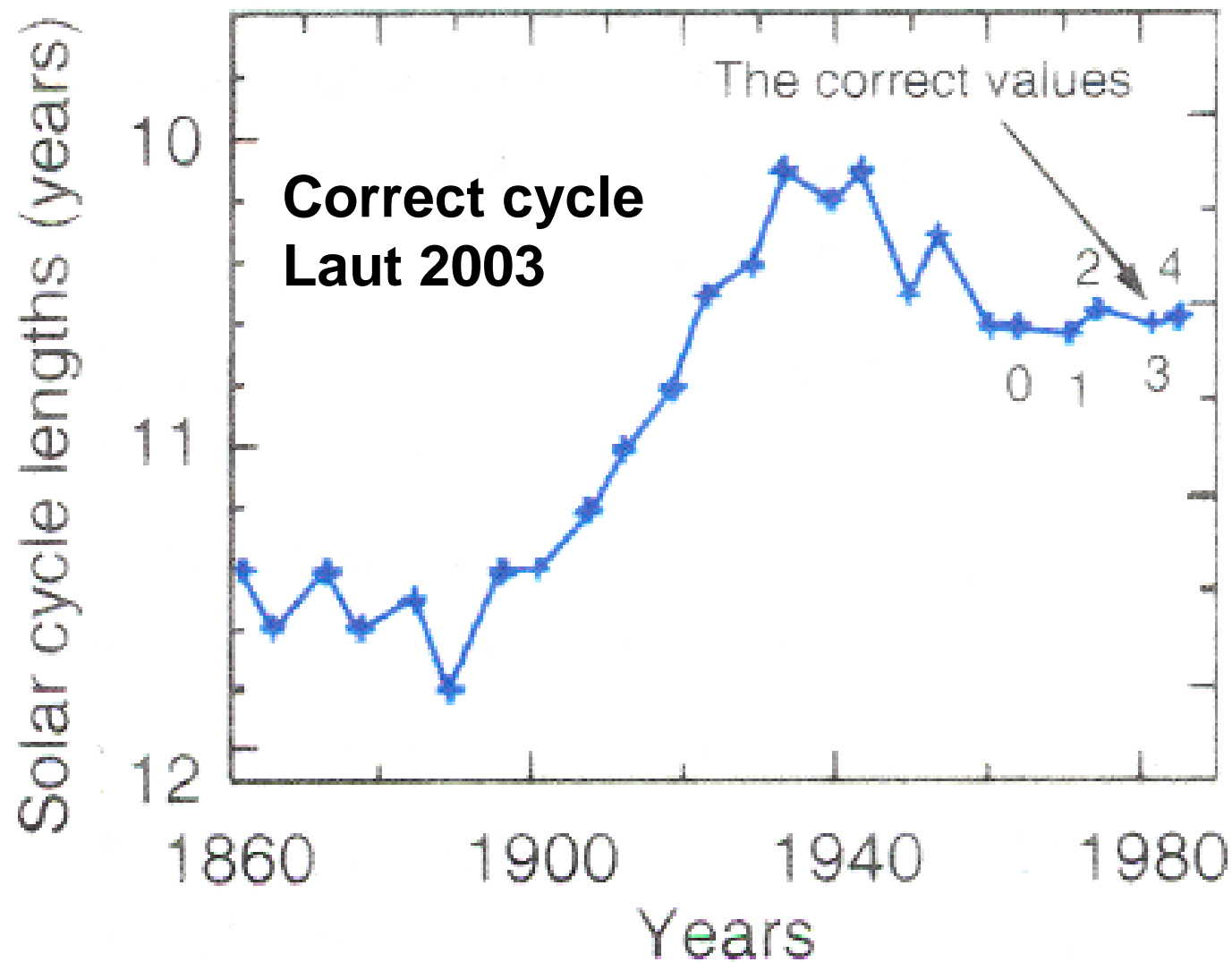
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False Assertions: Sun – Global Warming



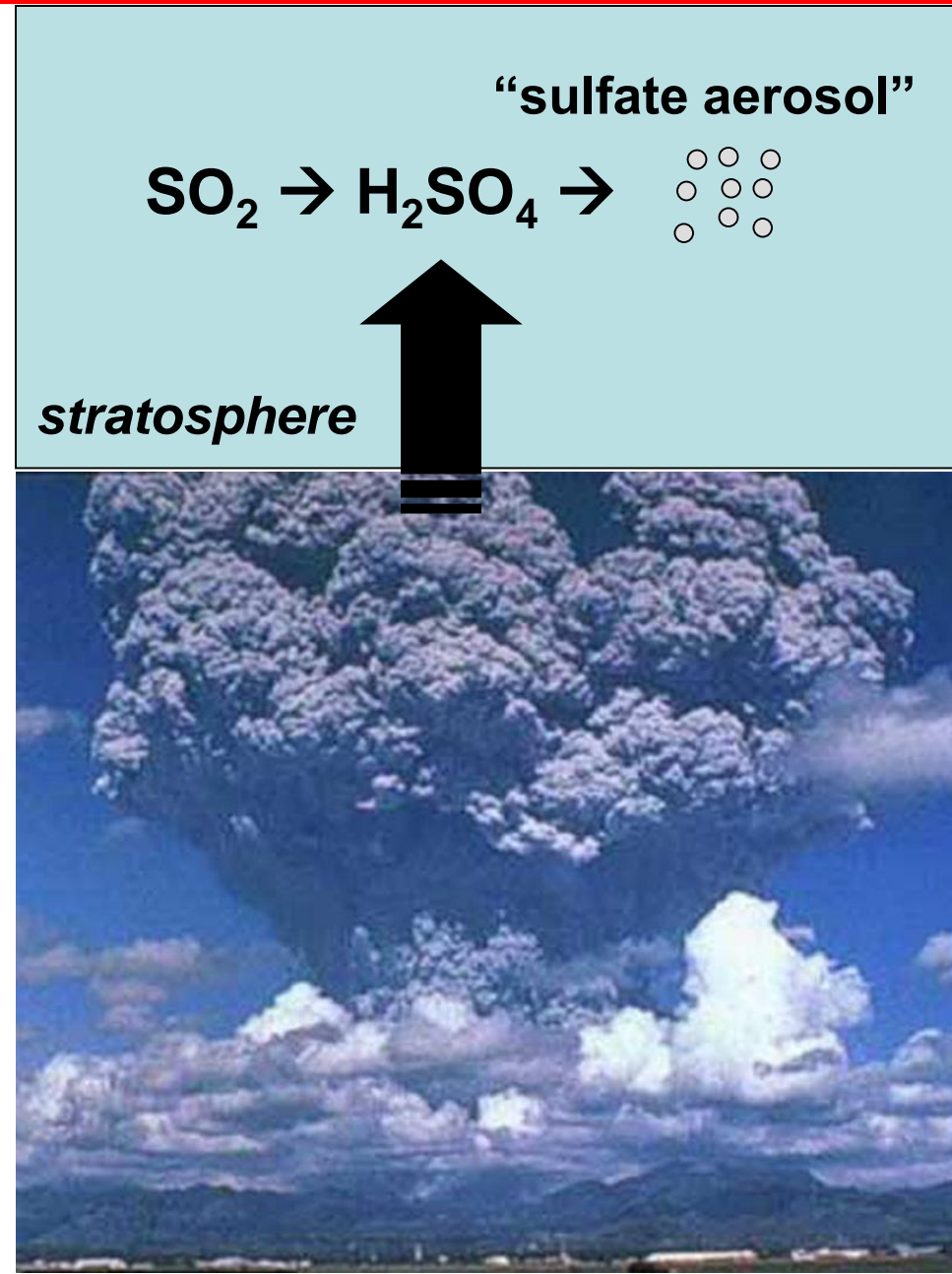
SOURCE: S. Baliunas and W. Soon / Astrophysical Journal

False Assertions: Sun – Global Warming



Volcanic Aerosol Forcing (in stratosphere)

- 5 – 30% by volume of volcanic emissions are SO_2 or H_2S
- A single large eruption can inject 20 Mtons of S as SO_2 *into stratosphere*



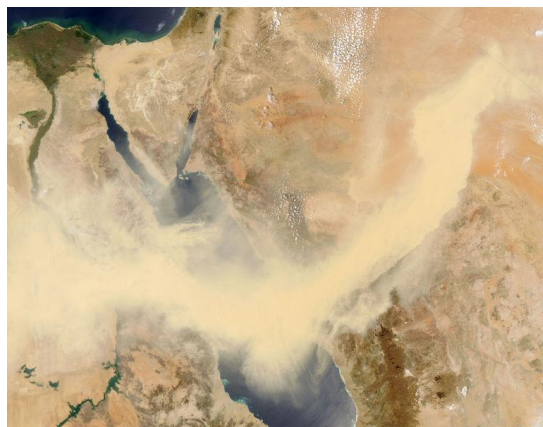
Sunrise over Texas From Space Shuttle

Stratospheric aerosol layer – a natural component of atmospheric albedo



Aerosol Particles aka Particulate Matter

- Suspended solids or liquid particles in air



Soil/desert dust



Sea spray



Smoke



Volcanoes



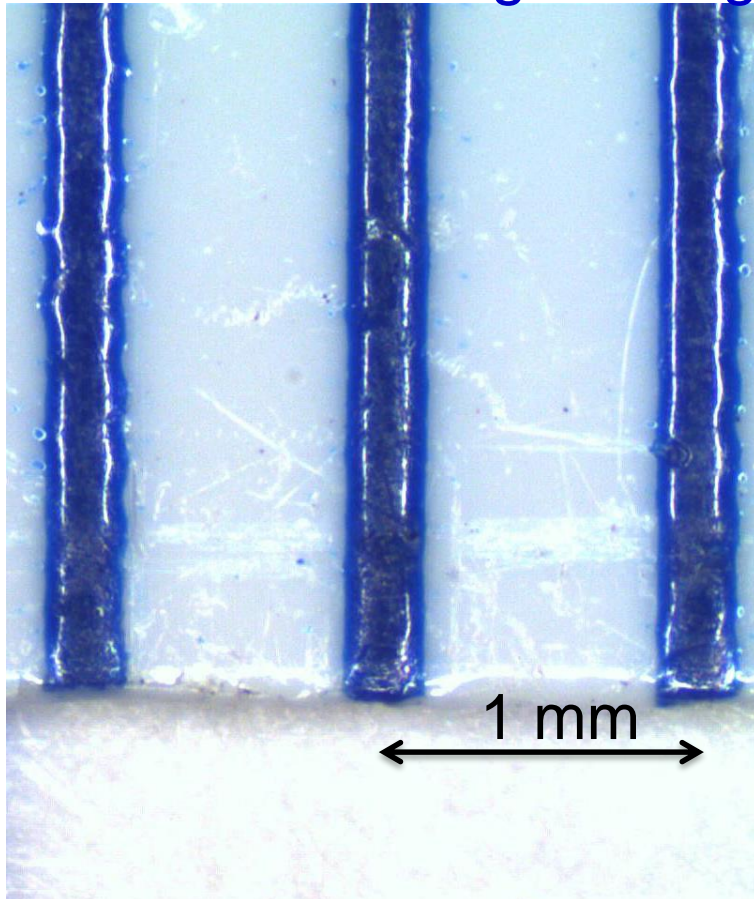
Fuel Combustion



Biogenic emissions

Aerosol particles sizes

Ruler scale through a magnifying glass:



Large aerosol particles to scale:



Big particle, e.g. pollen (0.1 mm = 100 μm)

"Smaller" particle, e.g. soil dust (10 μm)

Aerosol particle sizes

0.1 μm = 100 nm particle
(smoke, soot, or grown)



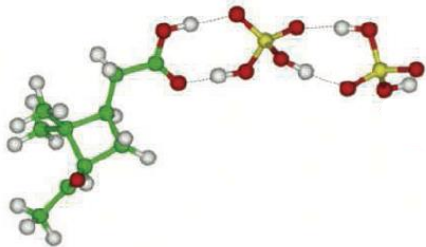
10 nm particle
(smoke, soot, virus, or grown)



A few molecules



500x zoom



1 nm

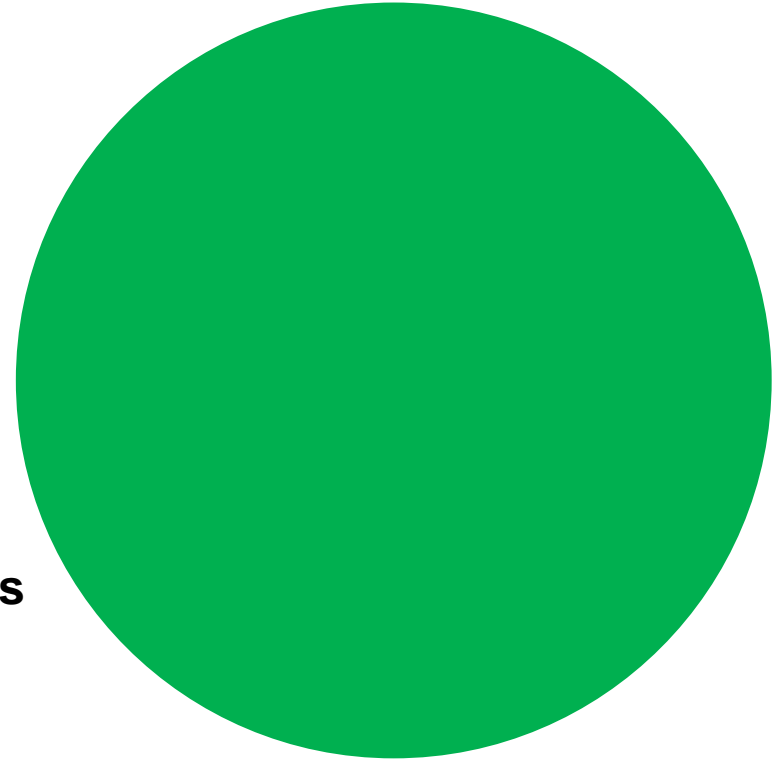
Dozens of molecules



70x zoom



3-4 nm



1 μm particle
(fine desert dust, smoke,
bacteria, pollution)

Soil dust particle, 10 μm



Aerosol “Haze”

Visual Range (hourly): **56 miles**
PM_{2.5} (24-hour avg): **9.25 µg/m³**
AQI: **30**

Seattle Visibility
09/15/14 03:01:34 PM



Visual Range (hourly): **139 miles**
PM_{2.5} (24-hour avg): **3.26 µg/m³**
AQI: **11**

Seattle Visibility
09/11/14 12:01:45 PM

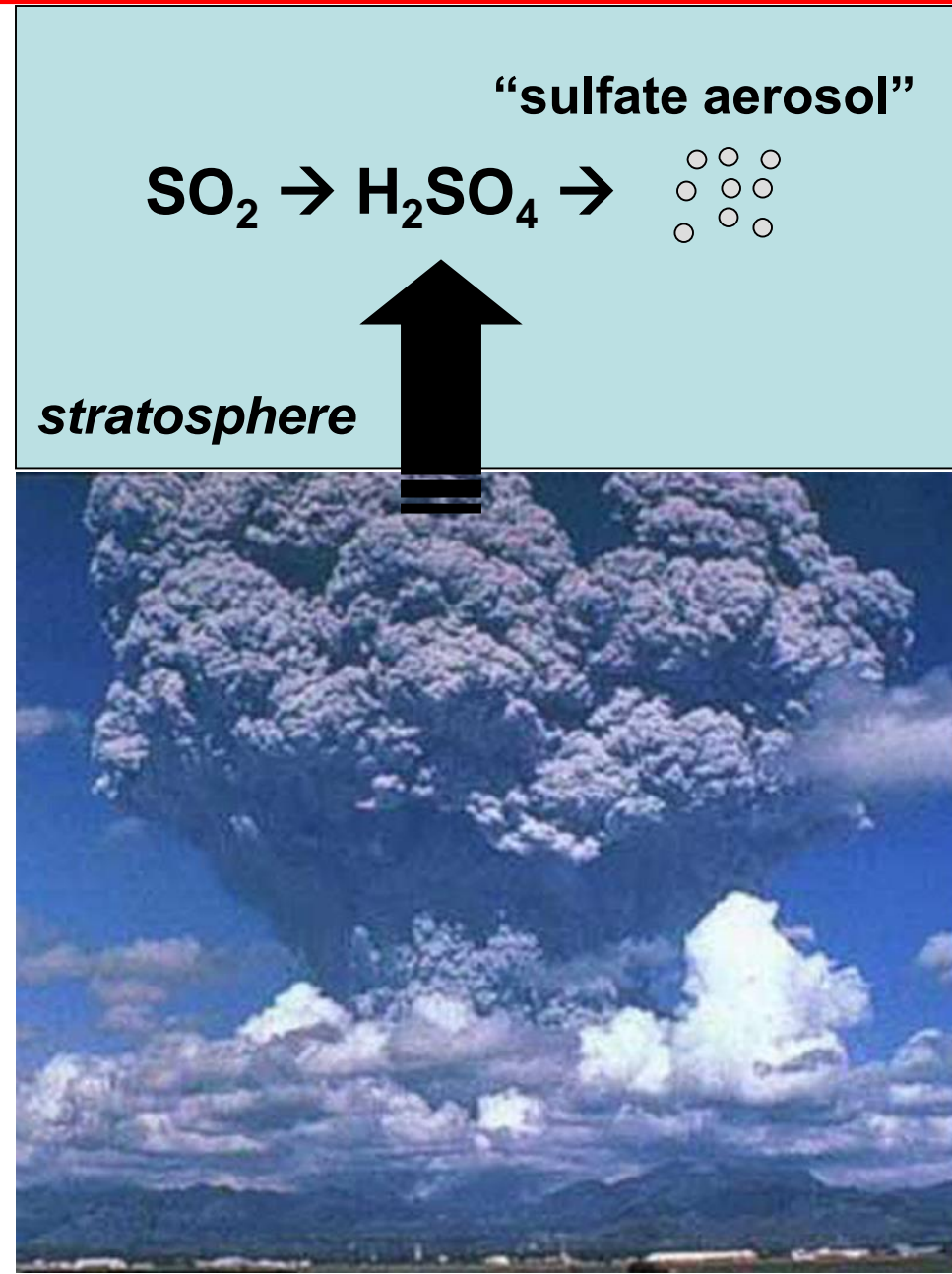


Puget Sound Clean Air Agency Visibility camera Queen Anne Hill (looking South)

Aerosol Particle Affects on Radiation

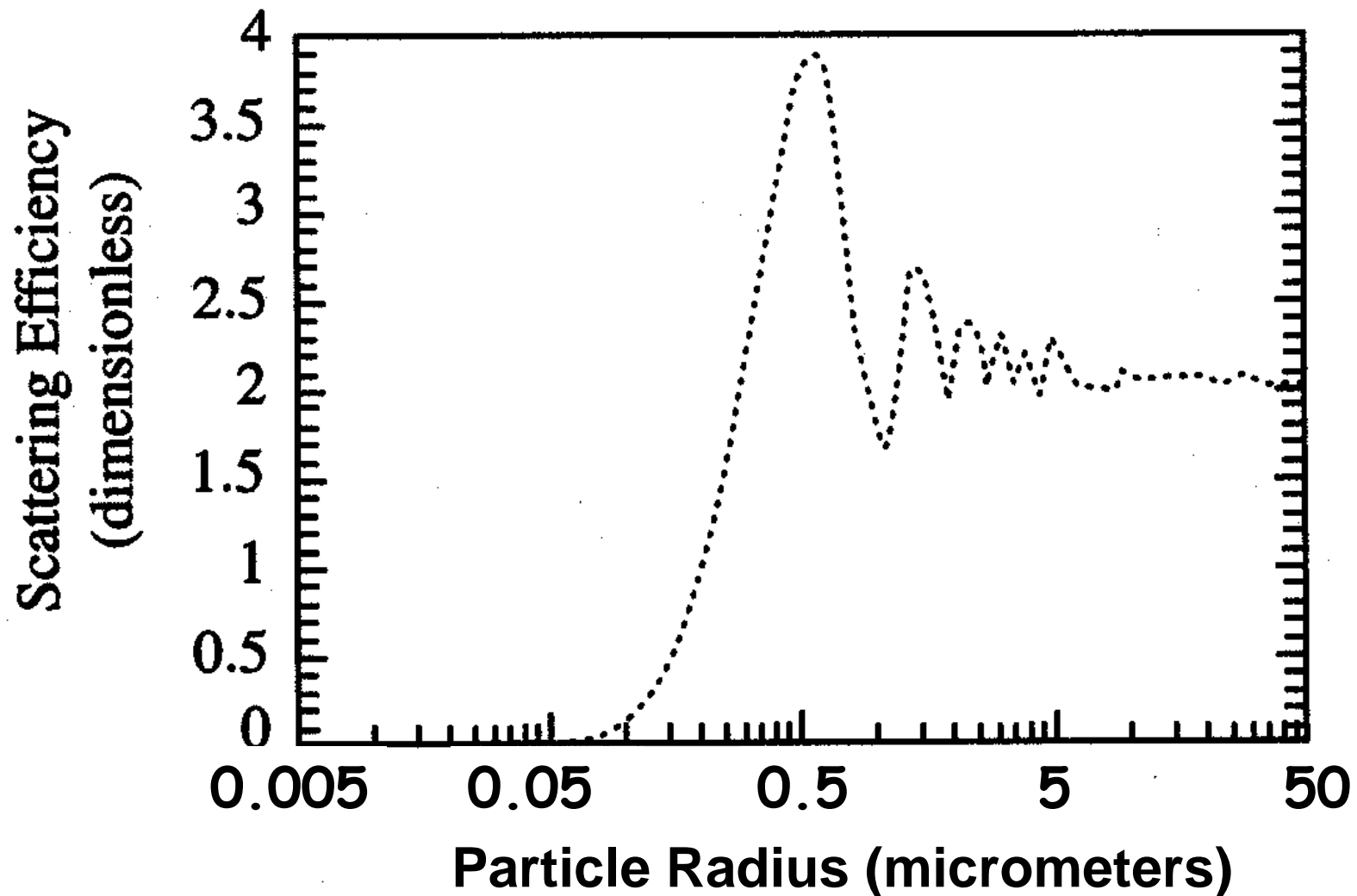
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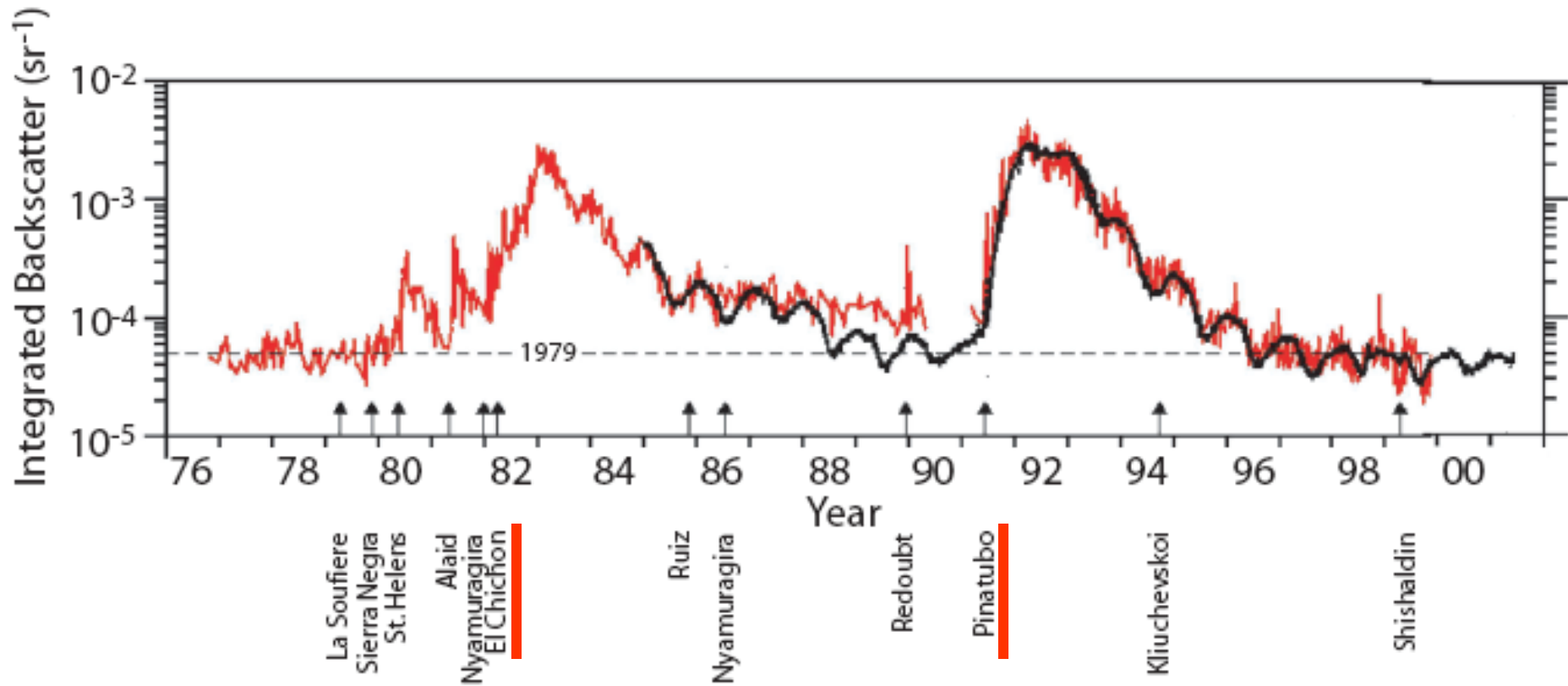


Scattering of Radiation Depends on Particle Size

Efficiency calculated assuming sunlight has wavelength of 0.5 μm



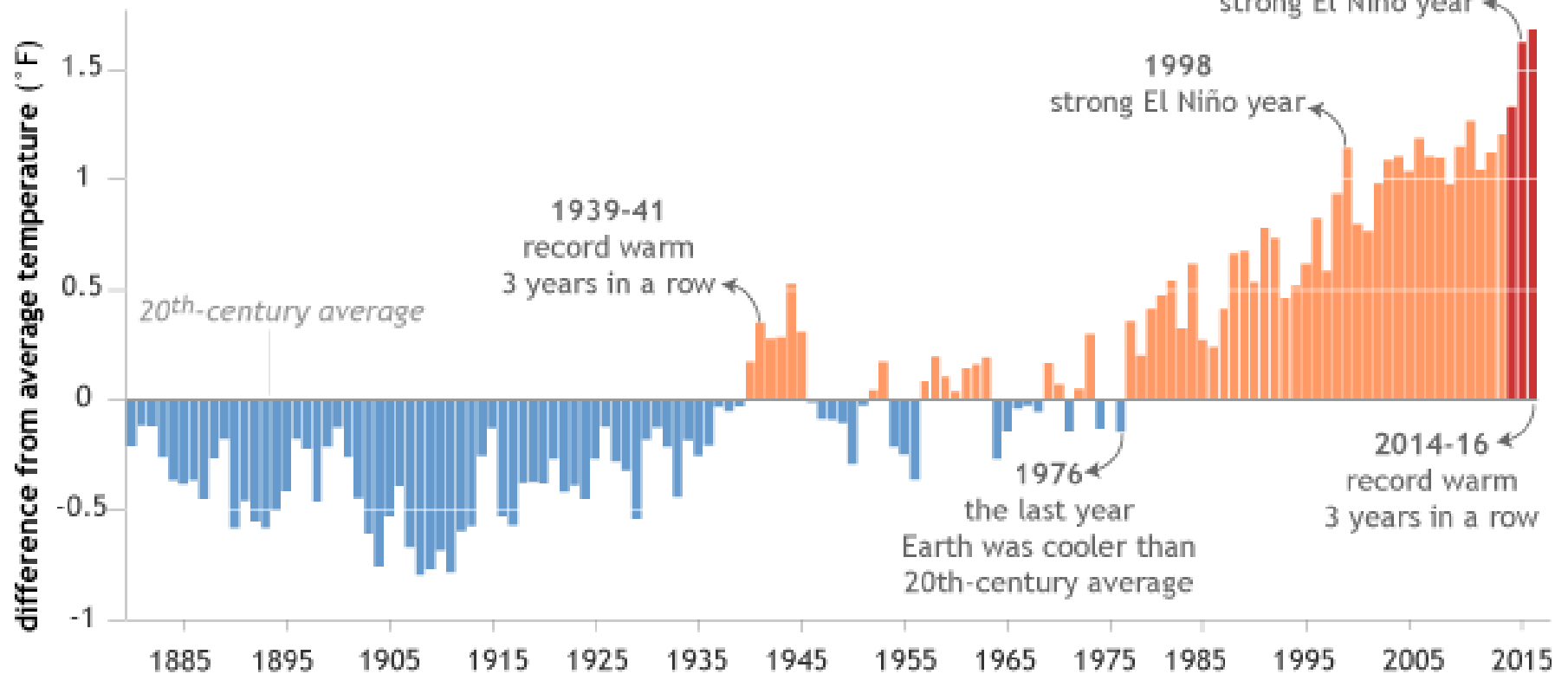
Stratospheric Aerosol Layer Backscatter vs. Time



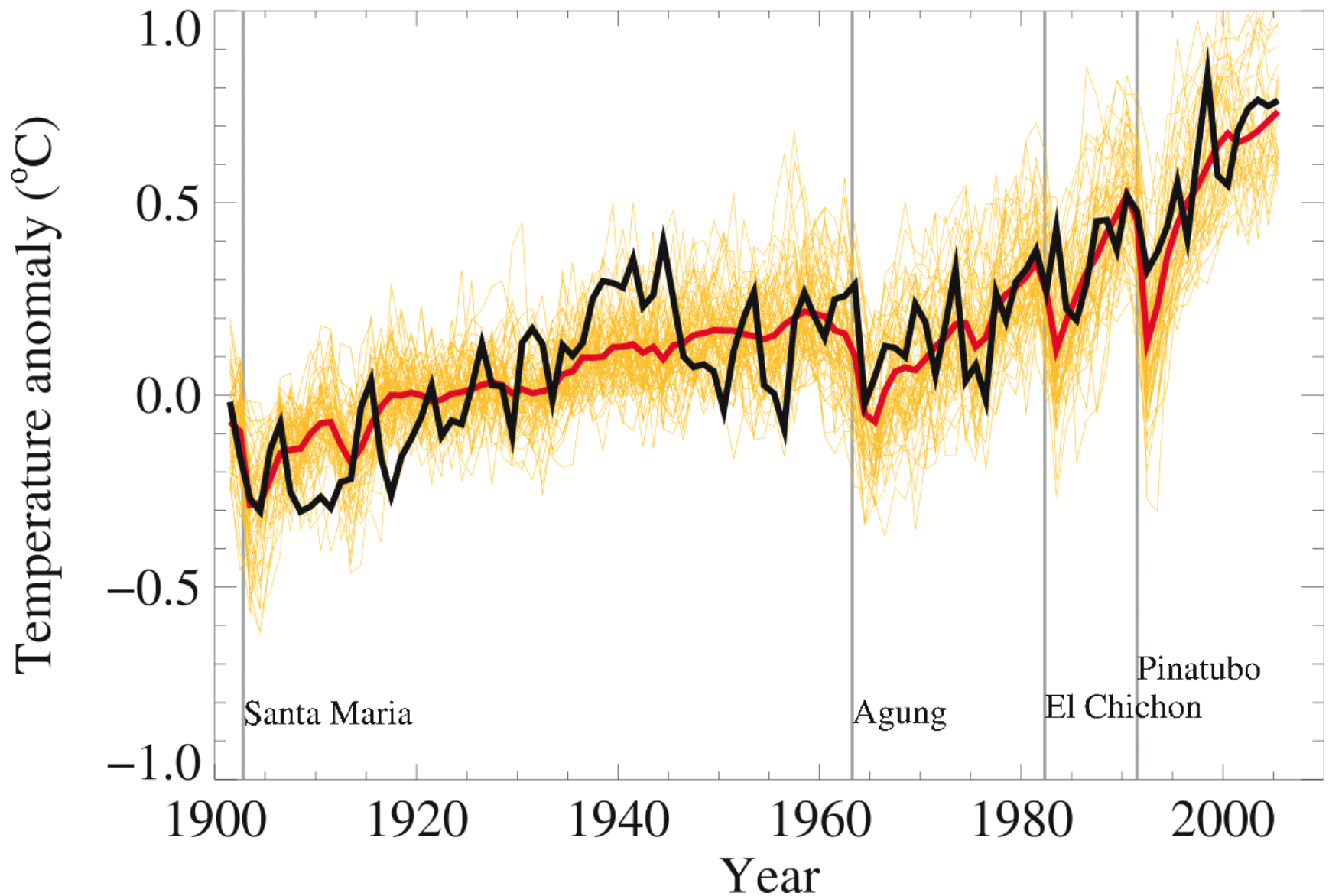
Volcanic eruptions

Modern Temperature Record

Earth's surface temperature, 1880-2016



T Response After Major Eruptions



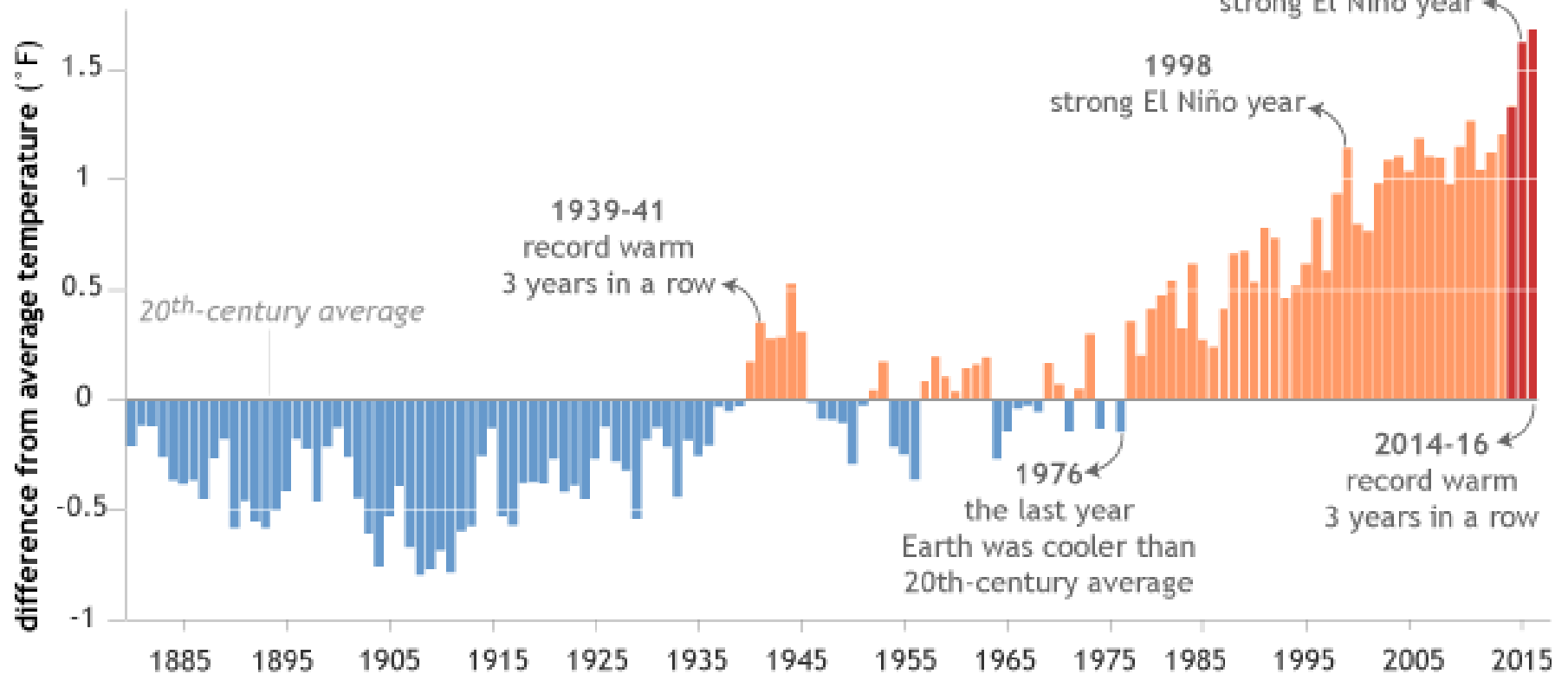
Volcanic Aerosol Forcing

Volcanic Aerosol Forcing

- Large volcanic eruptions in the tropical regions enhance the S.A.L.
- Enhanced S.A.L. means higher albedo, volcanic eruptions are $\Delta F < 0$. Noticeable effect on global average T.
- Effect on S.A.L. decays away after a few years (loss of particles from S.A.L.)

Modern Temperature Record

Earth's surface temperature, 1880-2016

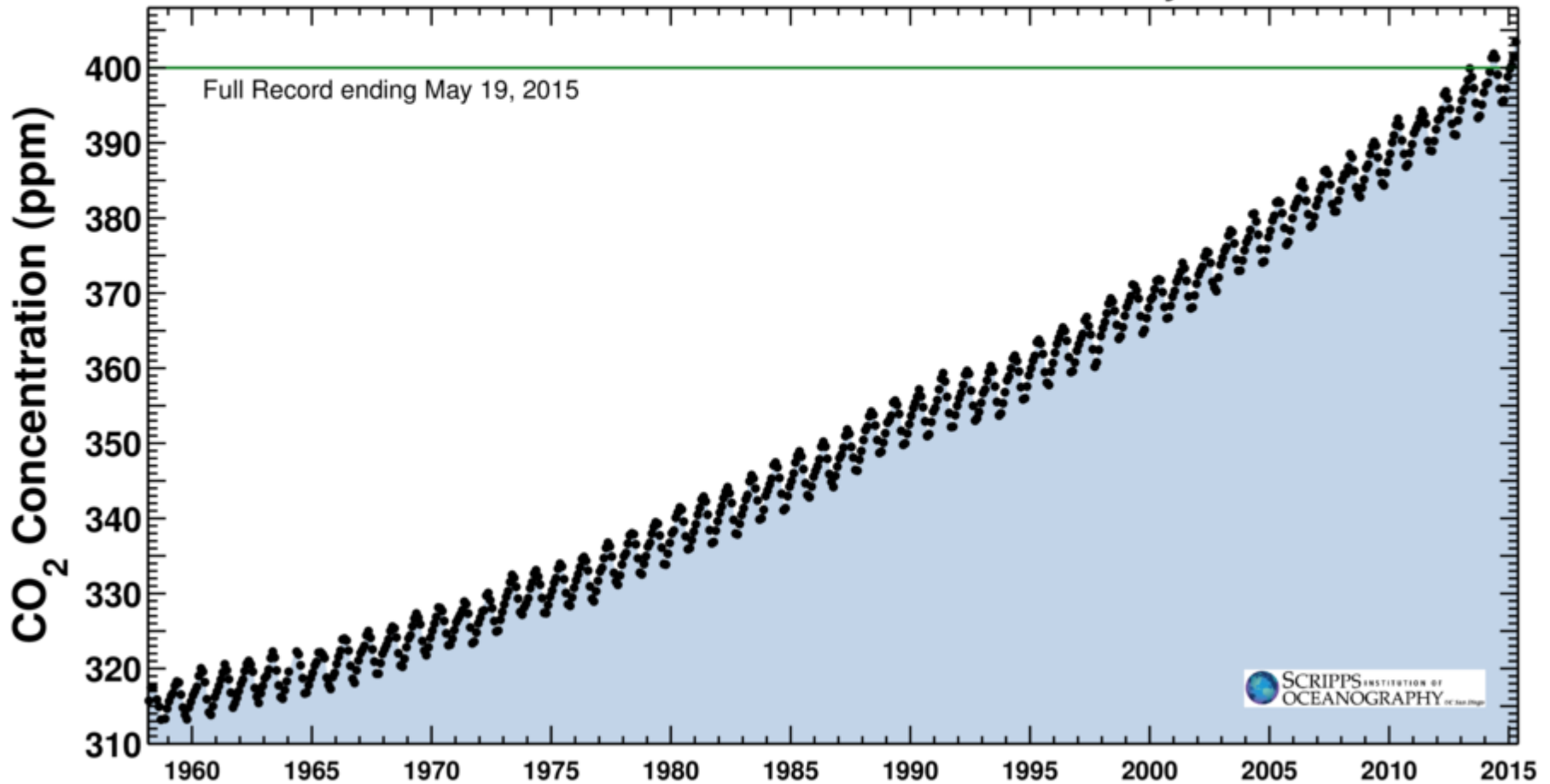


Anthropogenic GHG Forcing

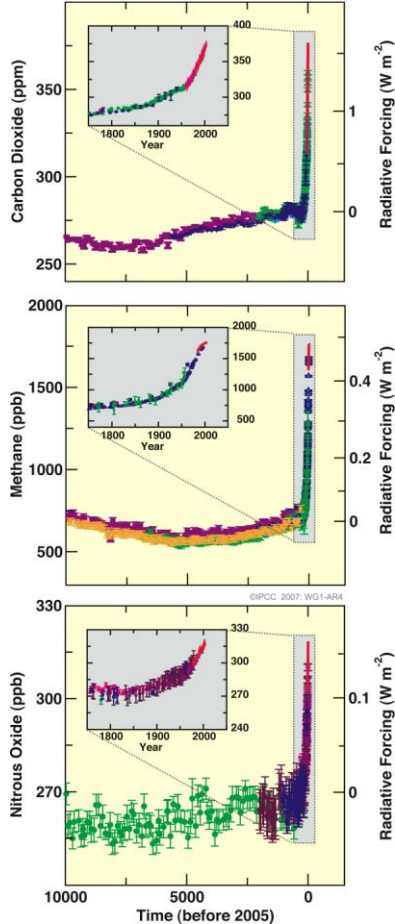
Latest CO₂ reading
May 19, 2015

403.88 ppm

Carbon dioxide concentration at Mauna Loa Observatory



Long-Lived GHG Concentrations



Carbon Dioxide: CO₂

- Enhanced by fossil fuel burning and land use change

Methane: CH₄

- Enhanced by agriculture and “natural gas” extraction/use

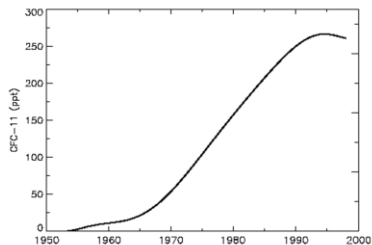
Nitrous Oxide: N₂O

- Enhanced by agriculture

Halocarbons: CFCs, HFCs

- Enhanced by industrial and consumer products

2.8 W/m²
forcing
since
1750



Recall: Poll Question

W Increasing GHG concentrations increase the atmosphere's absorptivity, "epsilon", which represents a

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

$$T_{Earth}^{sf} \sim \left[\frac{246}{\sigma \left(1 - \frac{\epsilon}{2} \right)} \right]^{\frac{1}{4}}$$

Positive Forcing

Negative Forcing

Positive Feedback

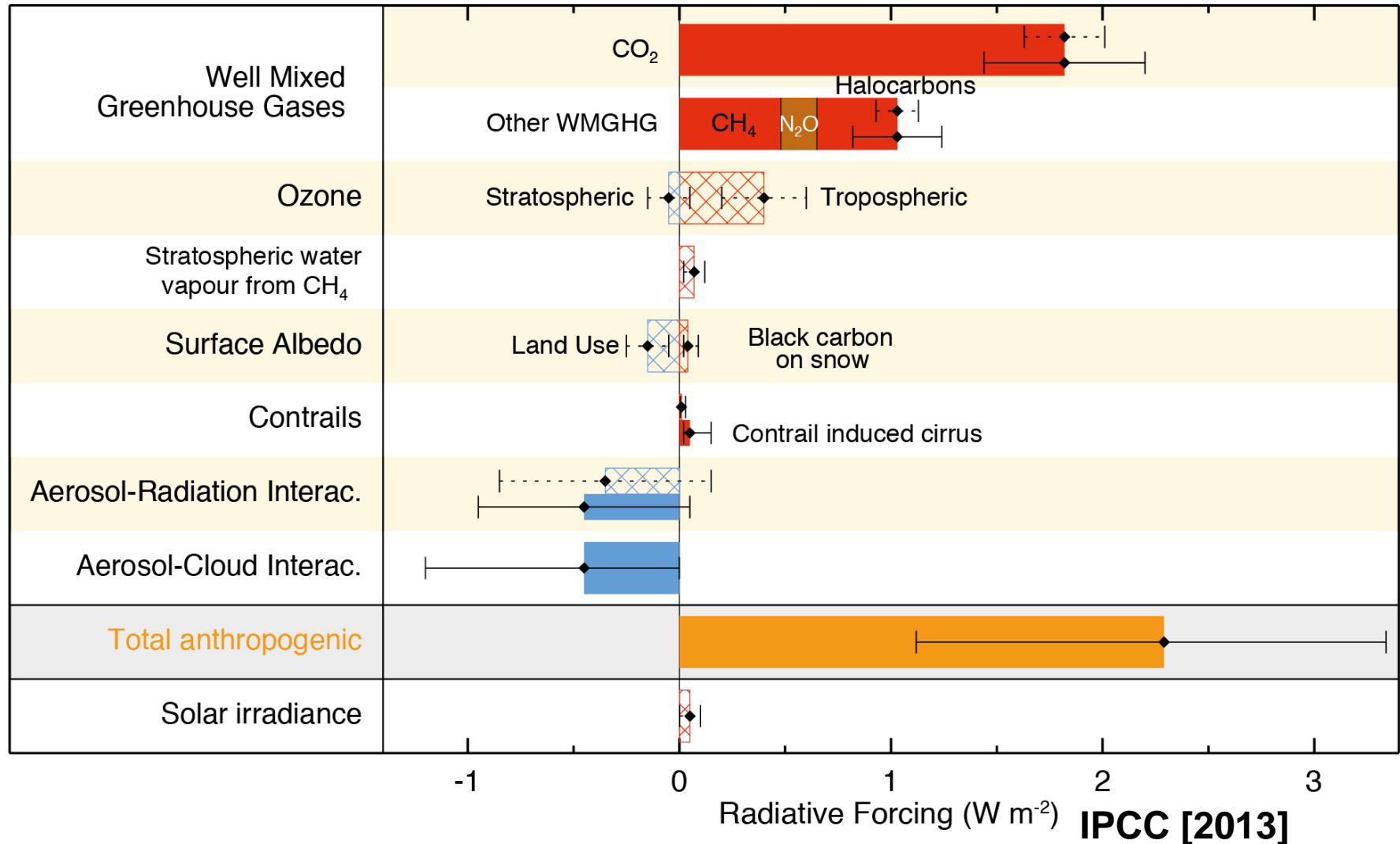
Negative Feedback

Total Results: 0

Anthropogenic Global Radiative Forcing of Climate

Radiative forcing of climate between 1750 and 2011

Forcing agent



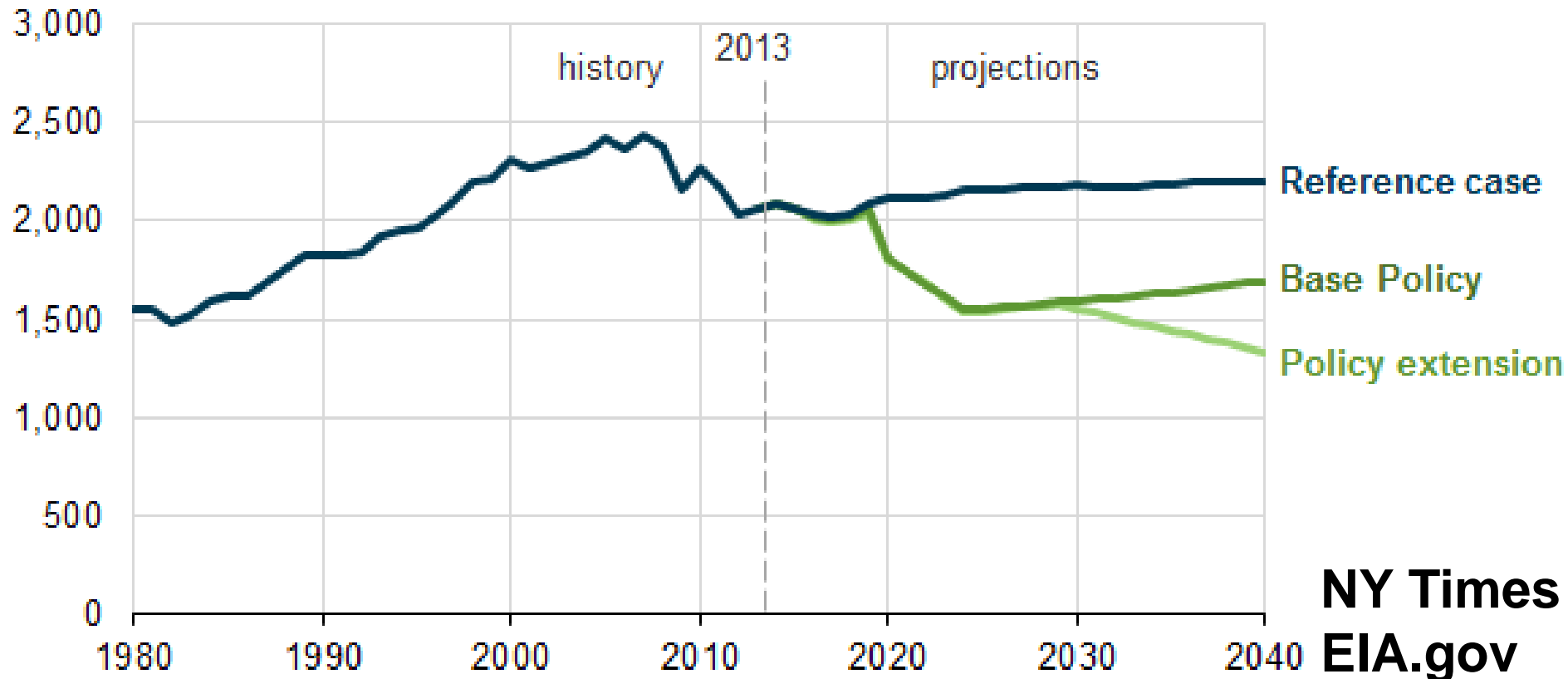
U.S. Proposed Policy

POLITICS

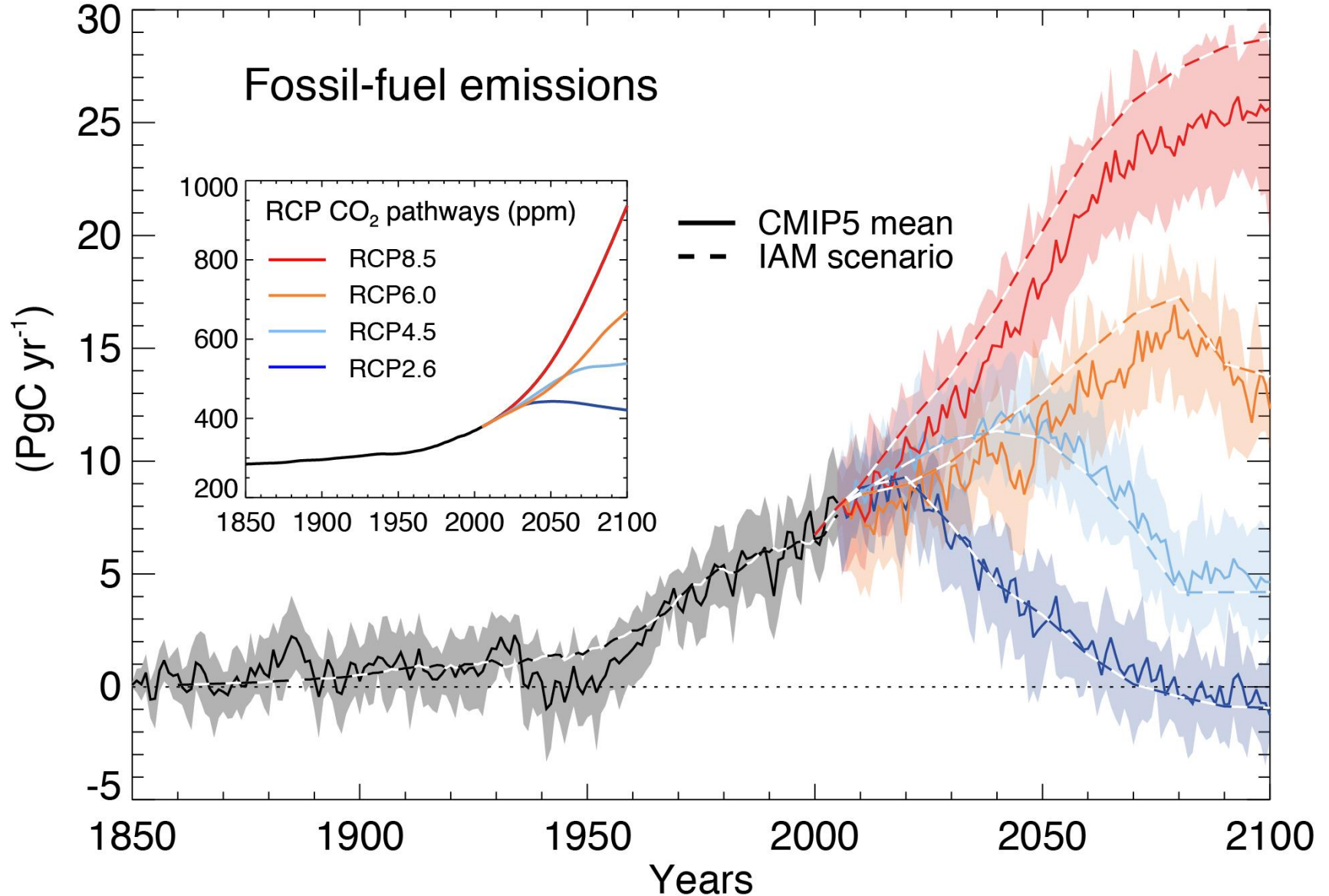
EPA Seeks to Cut Power Plant Carbon by 30 Percent

By THE ASSOCIATED PRESS JUNE 1, 2014, 7:41 P.M. E.D.T.

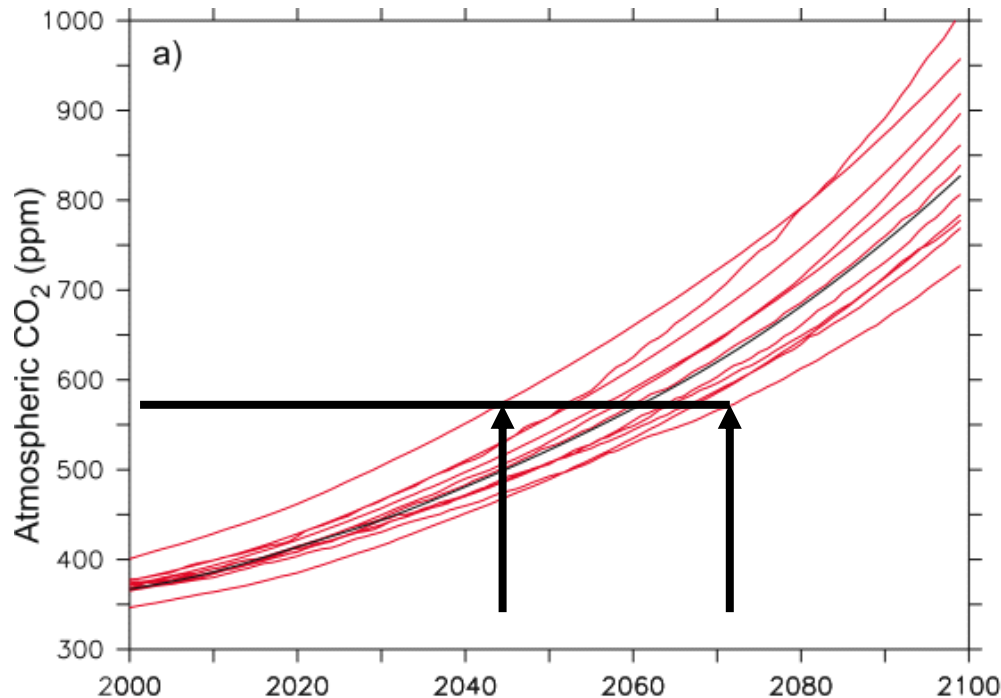
Carbon dioxide emissions from the electric power sector, 1980-2040
million metric tons



Projections of Future CO₂ Emissions



Future Atmospheric CO₂ concentrations



**One anthropogenic emission scenario
("business as usual") in many different
IPCC climate models**

**Range of model predictions suggest double
pre-industrial (2 x 280 ppm) by mid-century**

W

If all climate models use the same emissions scenario, why do they have rather different predictions of future CO2 concentrations?

 **Poll locked.** Responses not accepted.

A. Different assumptions about oceanic mixing

B. Different assumptions about net primary productivity

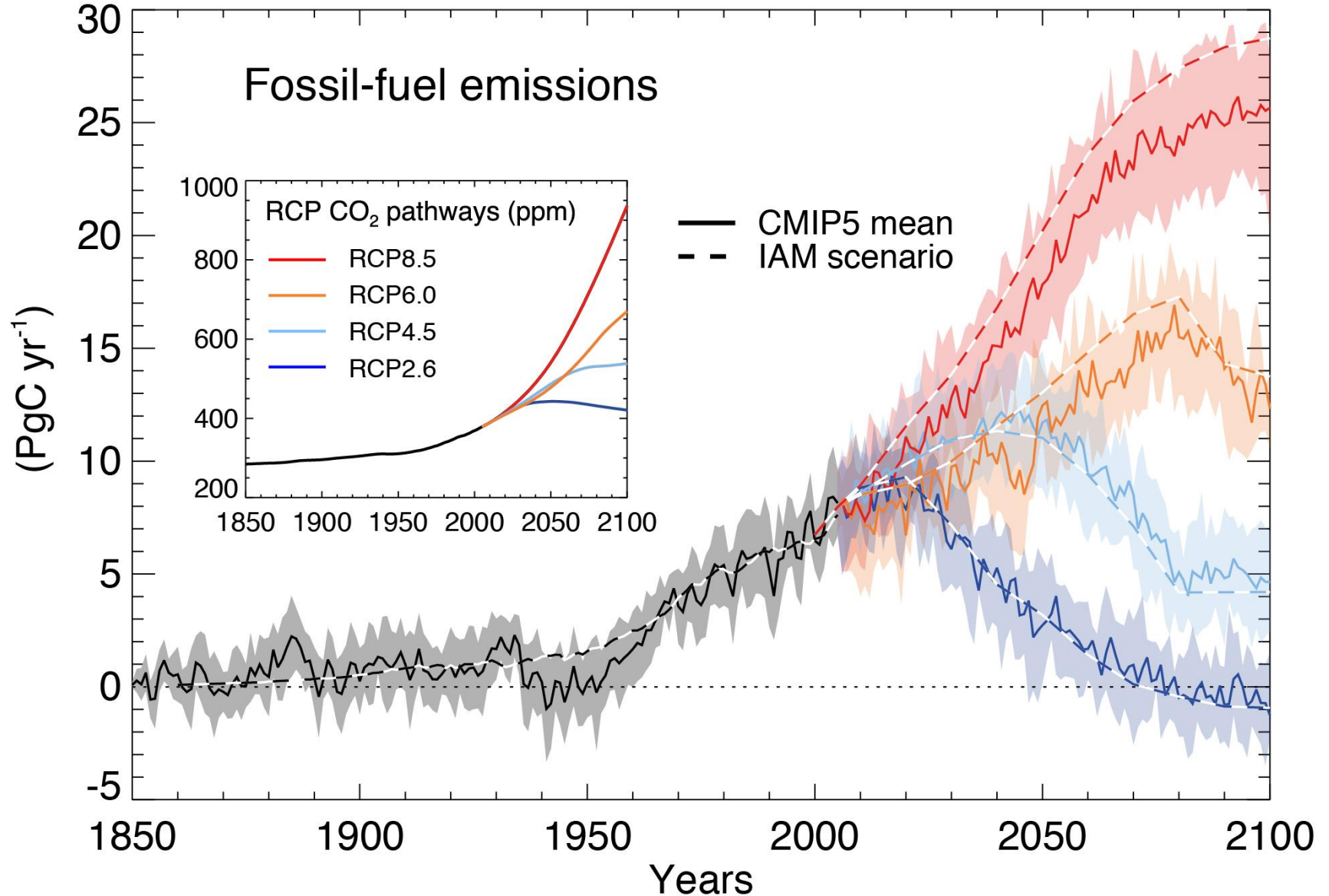
C. Different assumptions about oceanic chemistry

D. Different assumptions about land use change

E. All of the above

Total Results: 0

Projections of Future CO₂ Emissions



Anthropogenic Global Radiative Forcing of Climate

