What's up with Earth's Climate?

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Global Warming: The Science of Climate Change

David Archer

This class is an introduction to the science of global warming for students without a science background. Students will examine the evidence surrounding climate change from a variety of perspectives and approaches, and, in the process, gain a multidisciplinary understanding of the scientific process.

Workload: 4-7 hours/week

Taught In: English

Subtitles Available In: English

This Sesson Began
Sept. 29, 2014

Will begin again March 2015

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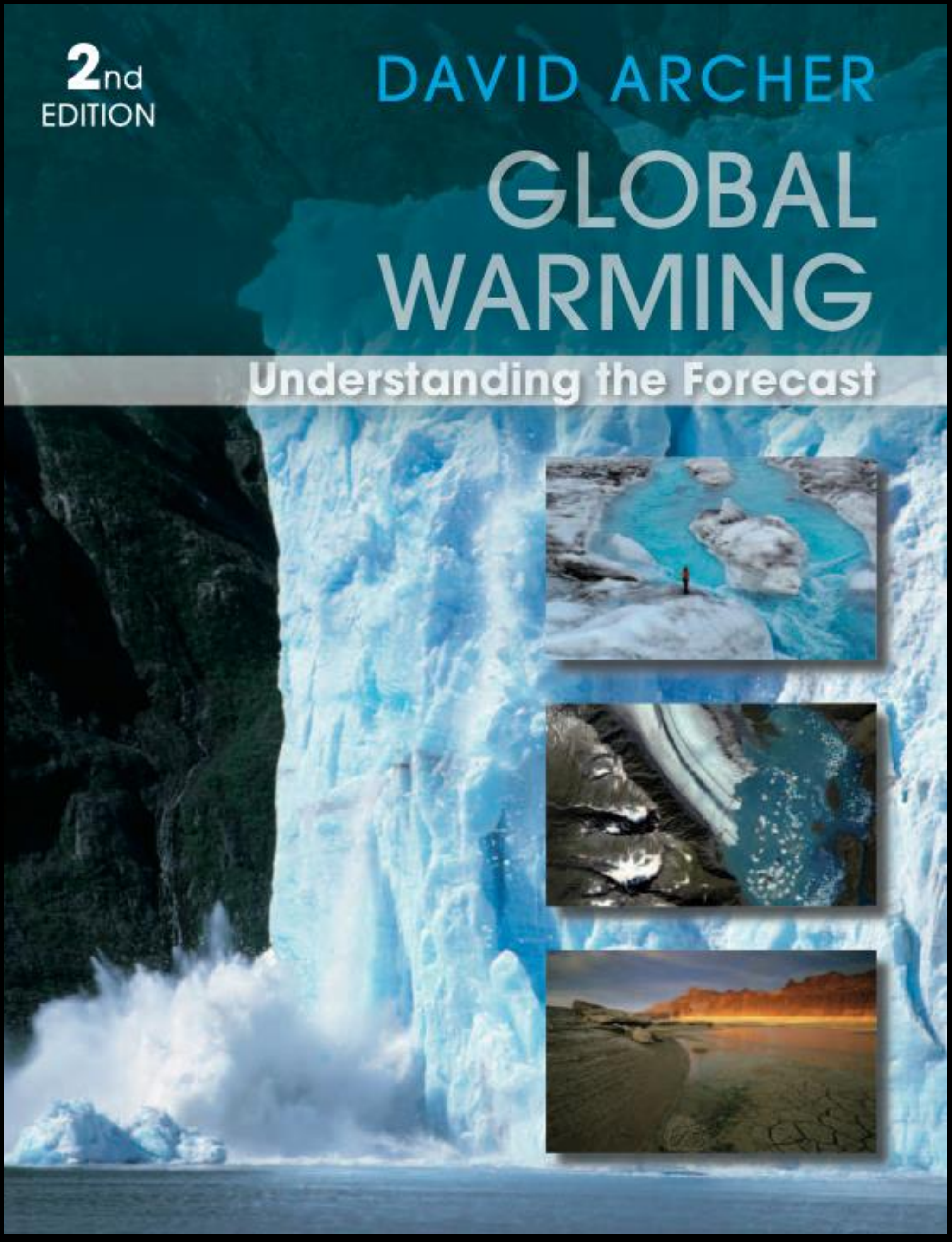
About the Instructor

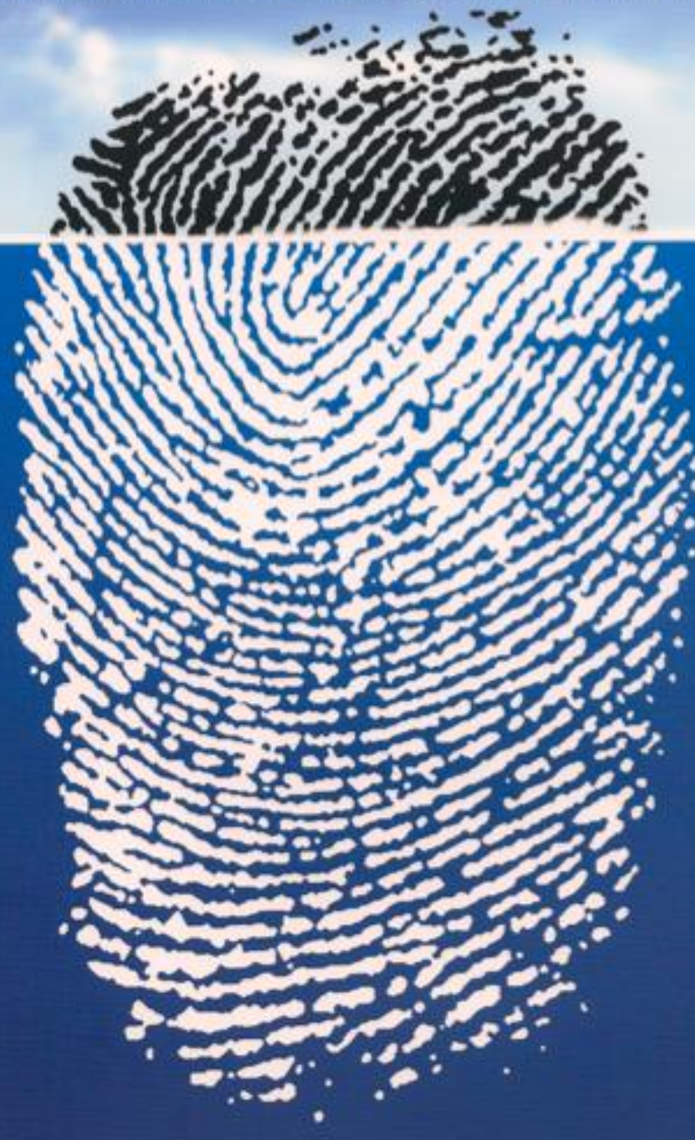
David Archer
The University of Chicago


2nd EDITION
DAVID ARCHER
GLOBAL WARMING
Understanding the Forecast

DAVID ARCHER

THE LONG THAW

HOW HUMANS ARE CHANGING THE NEXT 100,000 YEARS OF EARTH'S CLIMATE

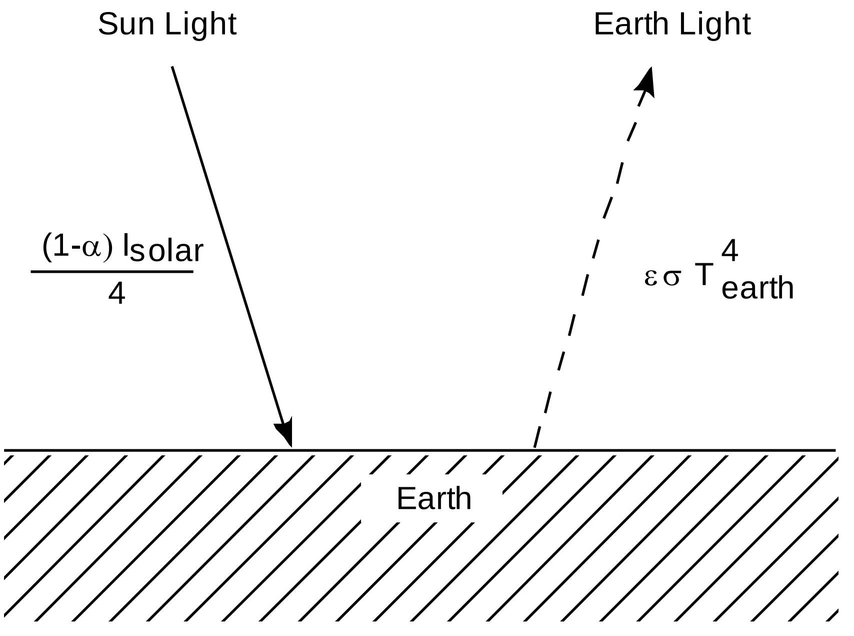


Other Good Books

Six Degrees by Mark Lynas

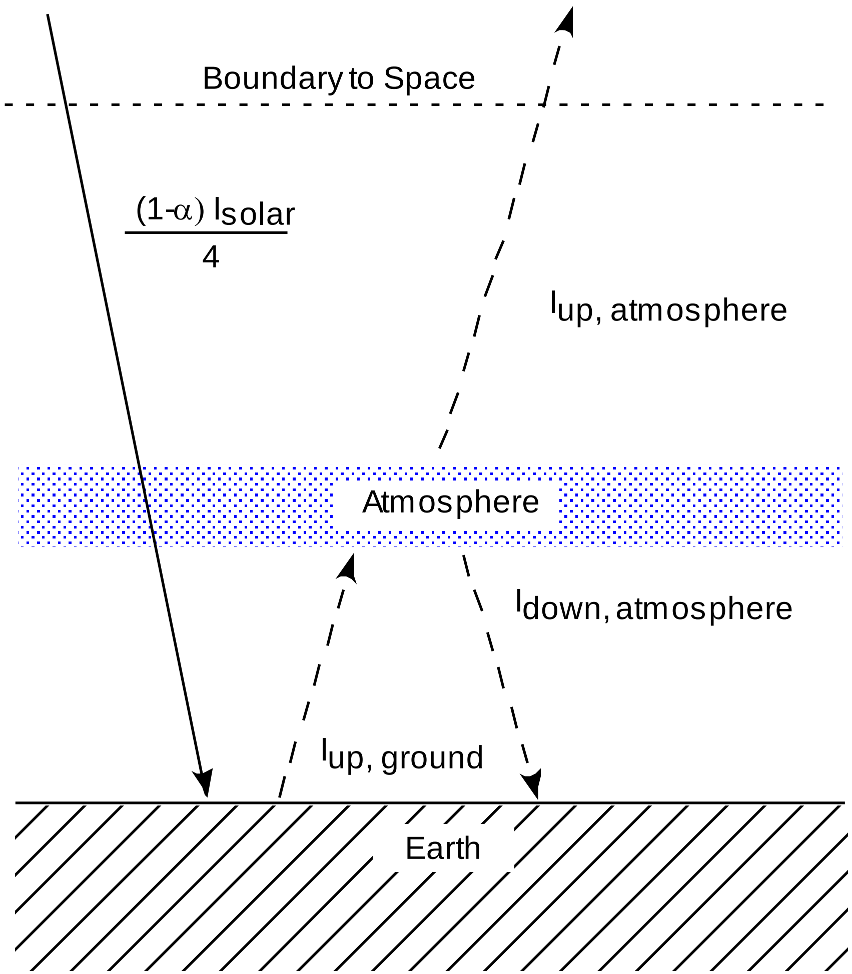
Alternative Energy Without All the Hot Air
David MacKay
available for free pdf download

Energy Balance of a Bare Rock



$$T_{earth} = 259\ \text{K} = -14°\ \text{C} = 6°\text{F}$$

A Planet with an Atmosphere



T_{atm} = 259 K

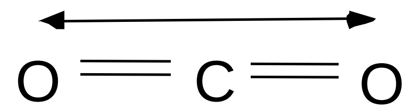
T_{earth} = 303 K
= 86° F

What Makes a Greenhouse Gas?

Resting State

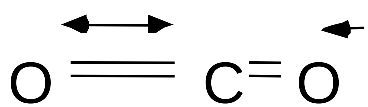
No Resting Dipole

Symmetric Stretch



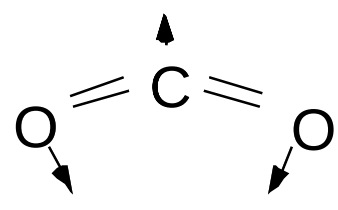
IR Inactive

Asymmetric Stretch



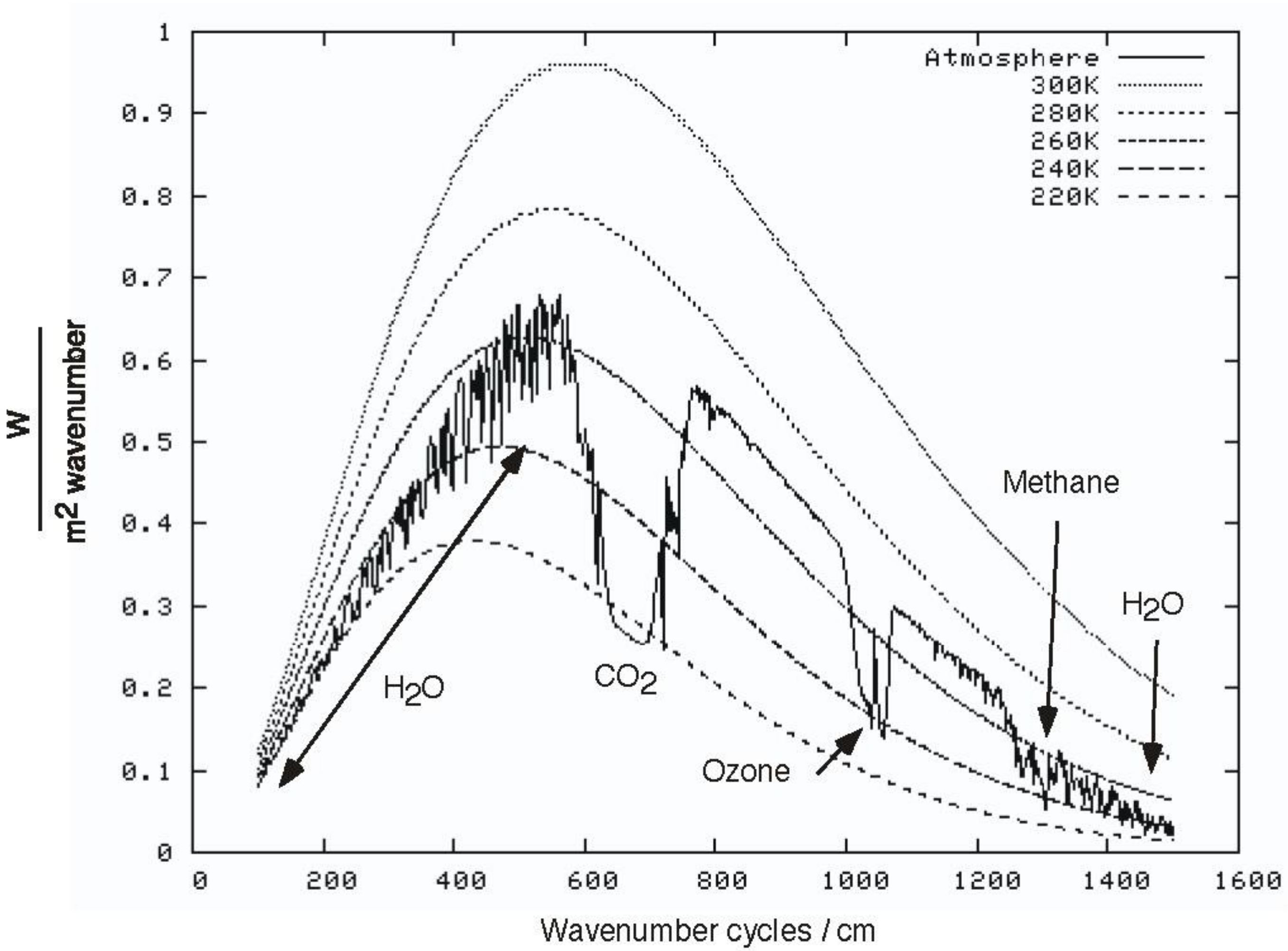
$2349\ cm^{-1}$

Bend



$660\ cm^{-1}$

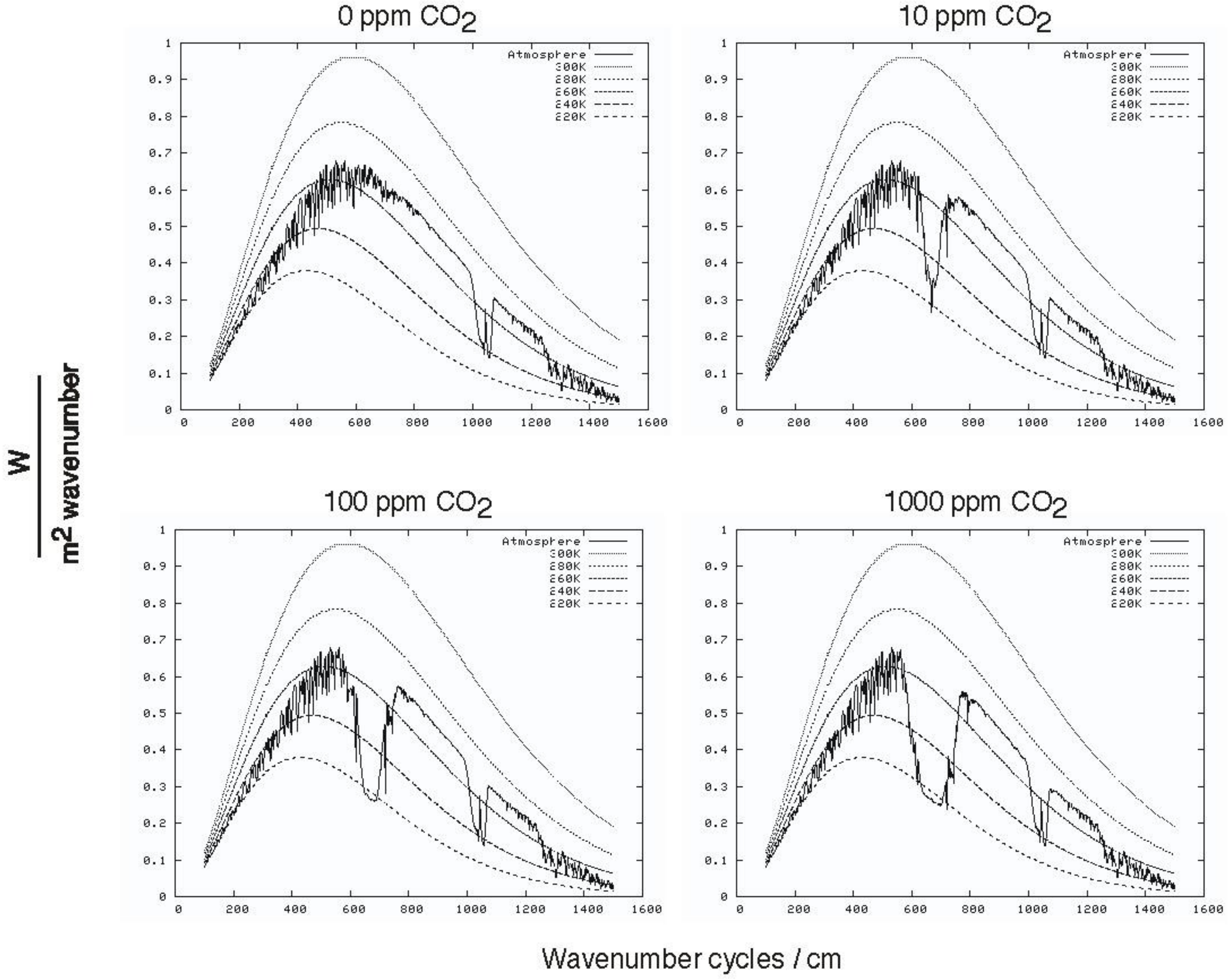
Earth's outgoing infrared spectrum

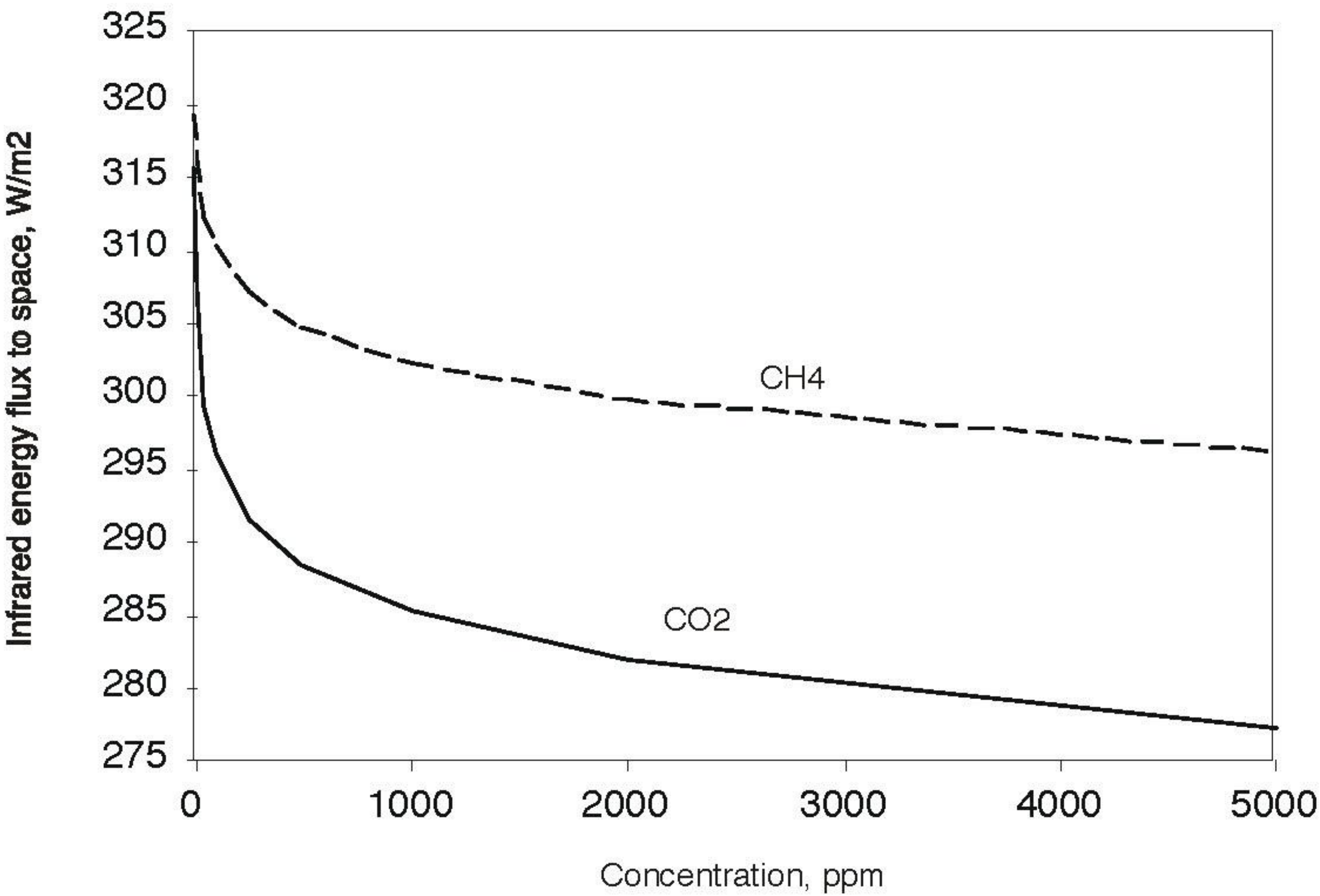


CO_2 absorbs where the light is.

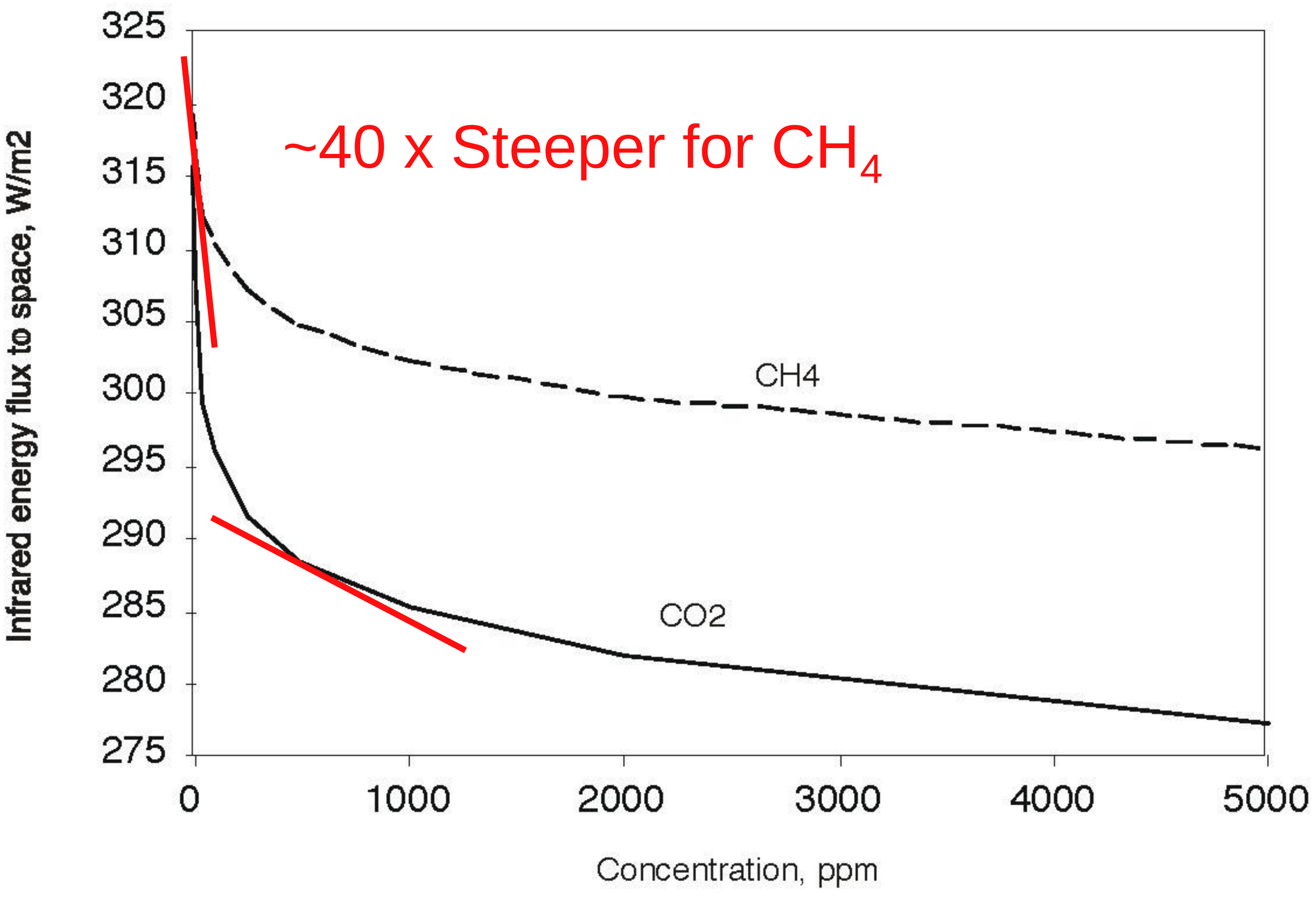
CH_4 is off in the wing.

The band saturation effect





325
320
315
310
305
300
295
290
285
280
275
0
1000
2000
3000
4000
5000
Infrared energy flux to space, W/m2
Concentration, ppm
CH4
CO2



~40 x Steeper for CH_4
325
320
315
310
305
300
295
290
285
280
275
0
1000
2000
3000
4000
5000
Infrared energy flux to space, W/m2
Concentration, ppm
CH4
CO2

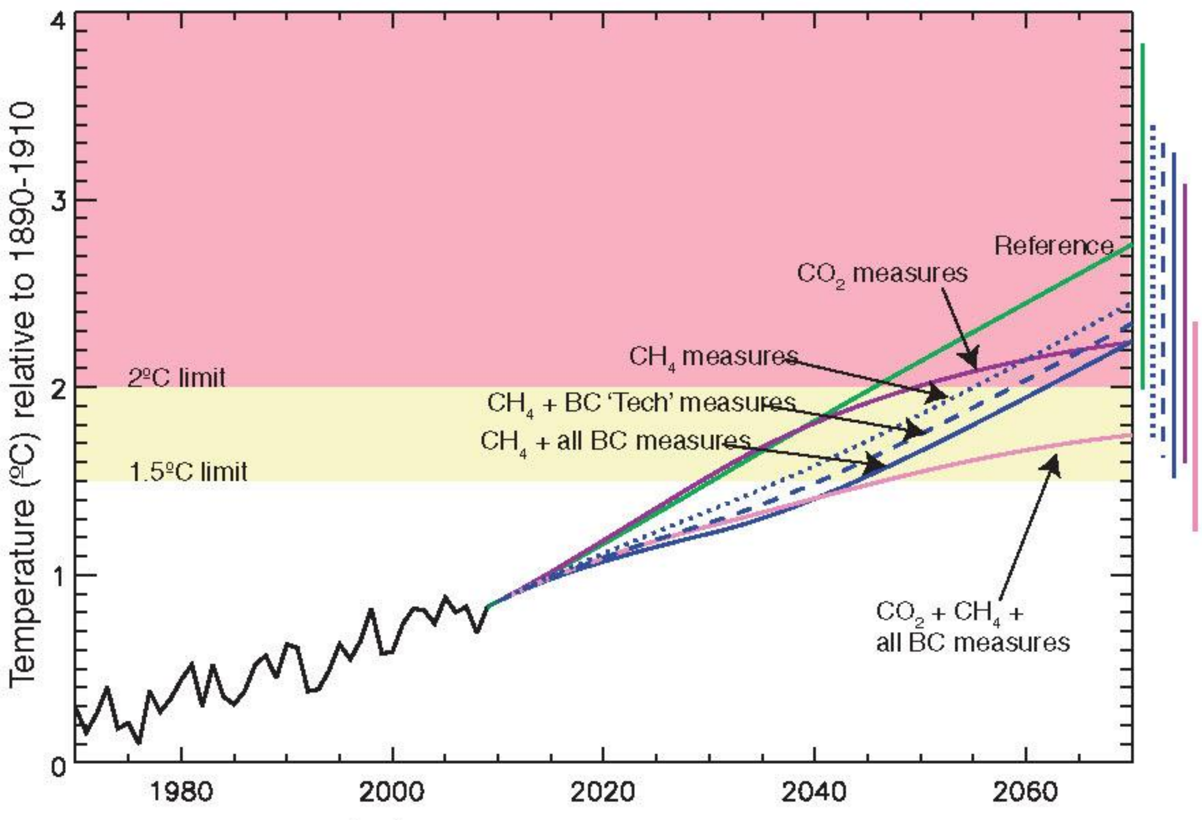


Fig. 1. Observed temperatures (*42*) through 2009 and projected temperatures thereafter under various scenarios, all relative to the 1890–1910 mean. Results for future scenarios are the central values from analytic equations estimating the response to forcings calculated from composition-climate modeling and literature assessments (*7*). The rightmost bars give 2070 ranges, including uncertainty in radiative forcing and climate sensitivity. A portion of the uncertainty is systematic, so that overlapping ranges do not mean there is no significant difference (for example, if climate sensitivity is large, it is large regardless of the scenario, so all temperatures would be toward the high end of their ranges; see www.giss.nasa.gov/staff/dshindell/Sci2012).

Shindell et al 2012

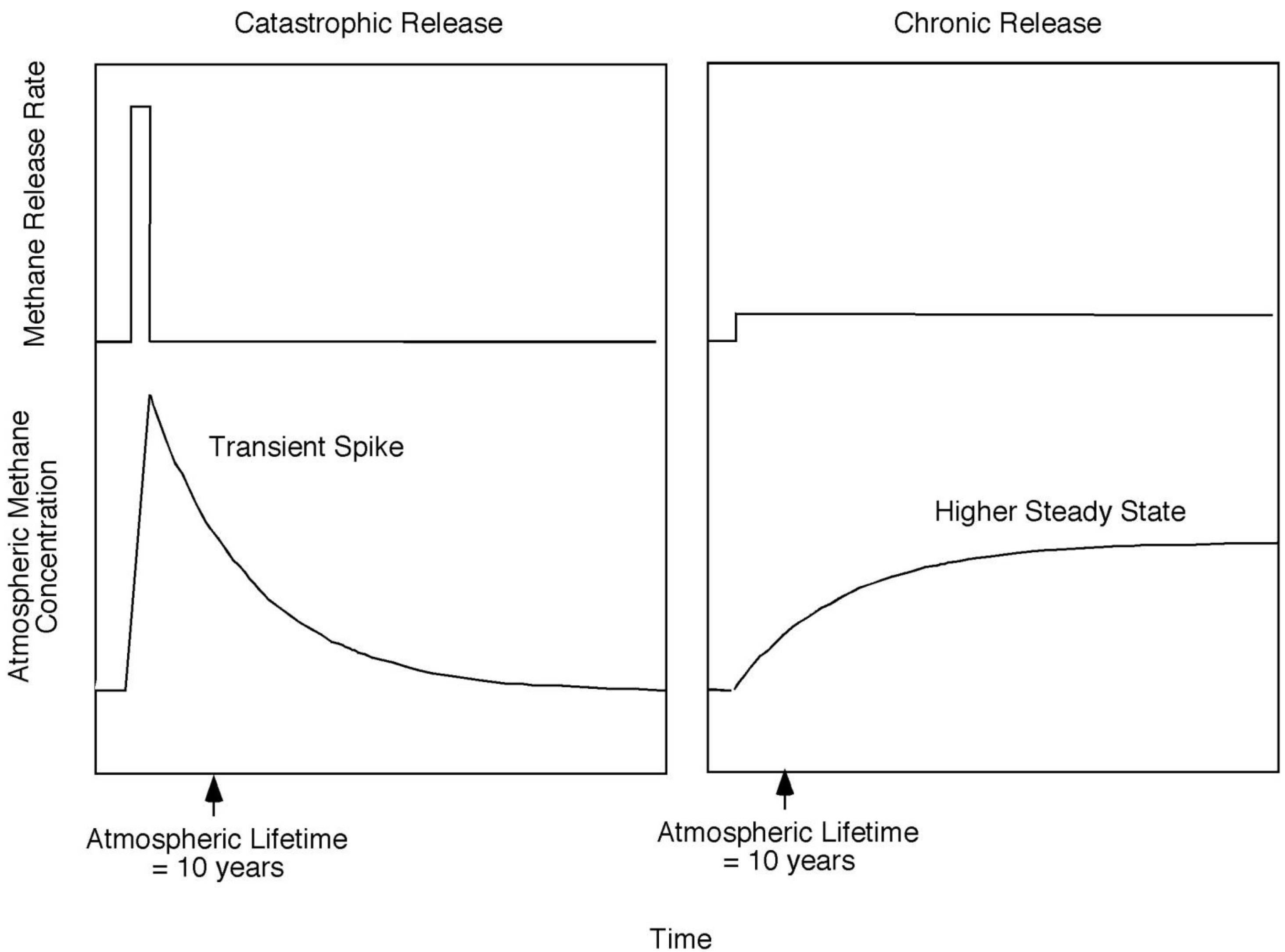
What Happens to Methane in the Atmosphere

$OH\cdot$

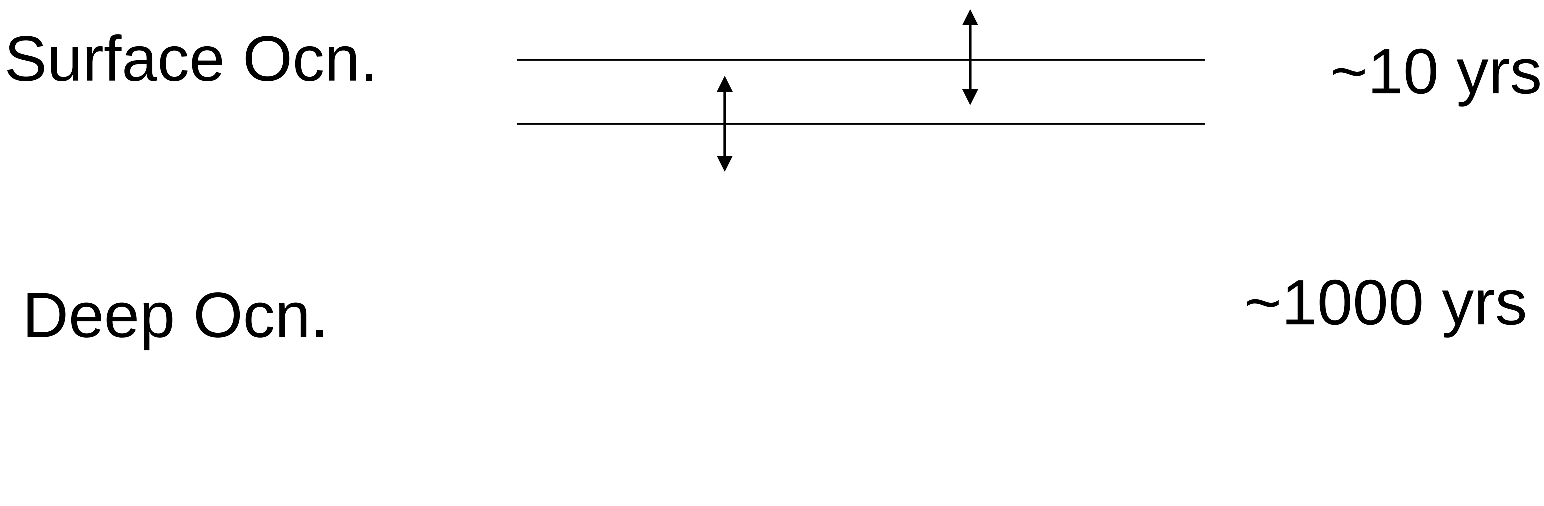
$CH_4 \longrightarrow CH_3\cdot \longrightarrow CO_2$

~ 10 years

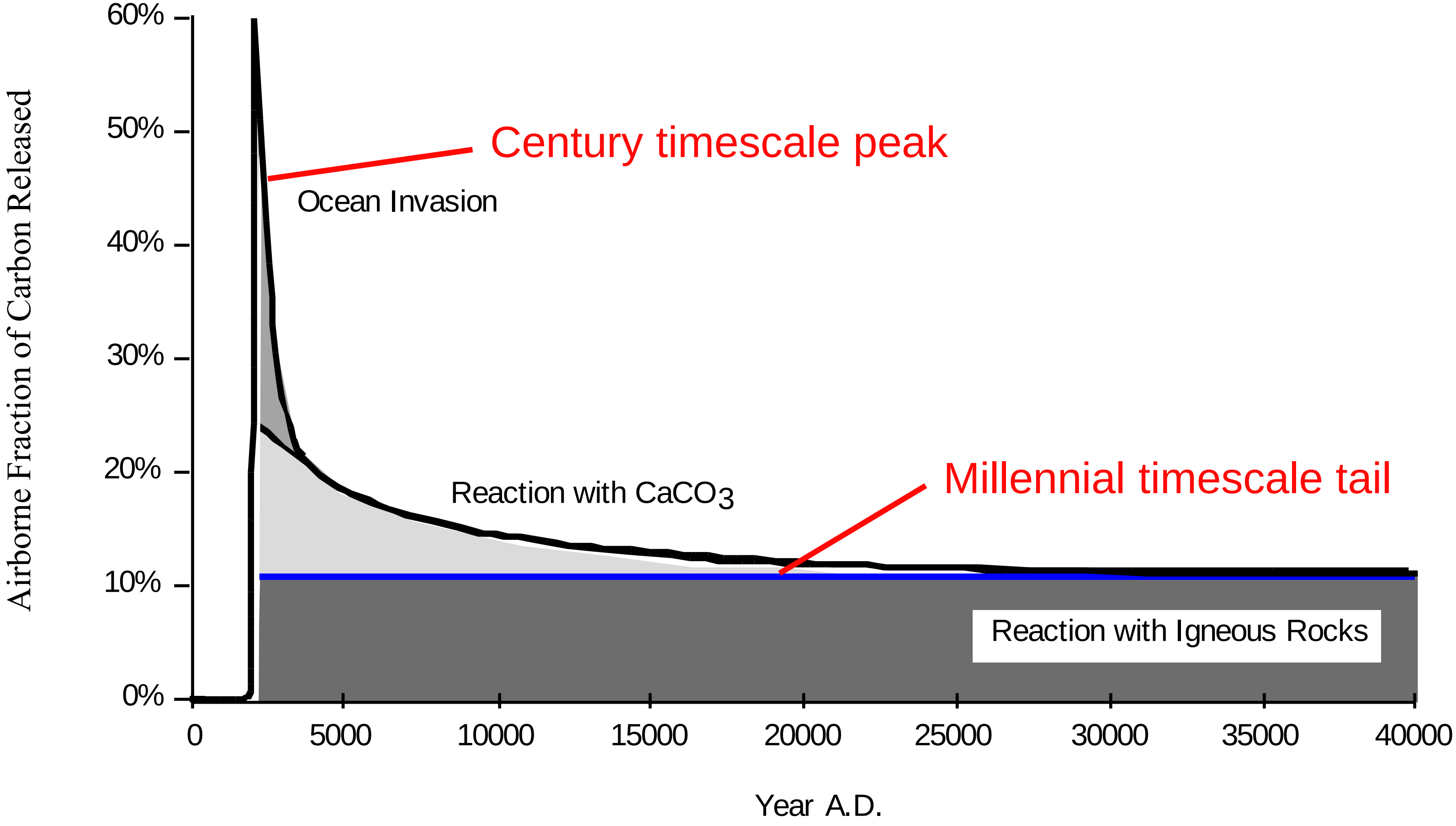
Methane Dynamics in the Atmosphere



Time scale for Earth's Temperature Response



What Happens to Fossil Fuel CO_2 in the Atmosphere



Stage I: CO_2 dissolves in the oceans

$$CO_2 + CO_3^{=} + H_2O \text{ <--> } 2\ HCO_3^{-}$$

Atmospheric CO_2
~600 Gton C

Ocean $CO_3^{=}$
~1800 Gton C

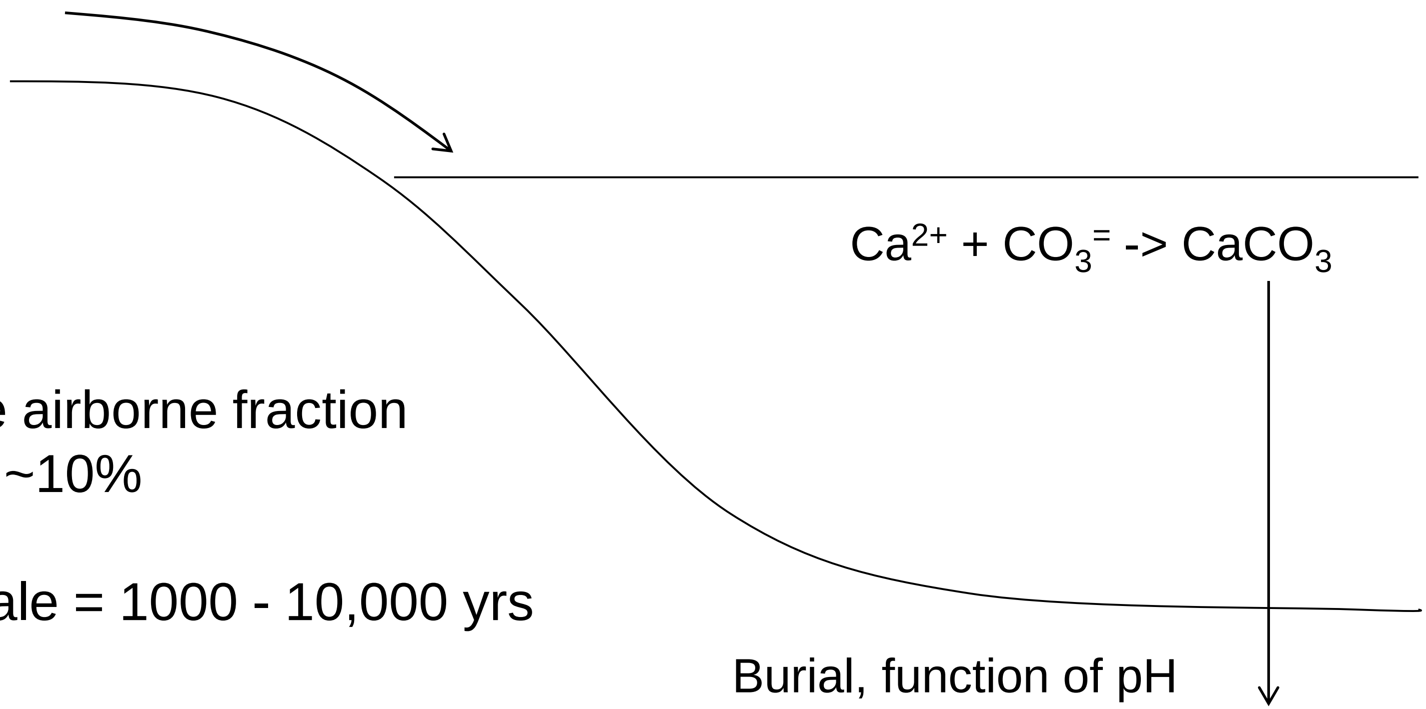
We expect a partitioning of ~1:3 between air and ocean

Time scale = 100’s - 1000 yrs

Gton C = 10^{15} g

Stage II: CO_2 is neutralized by $CaCO_3$

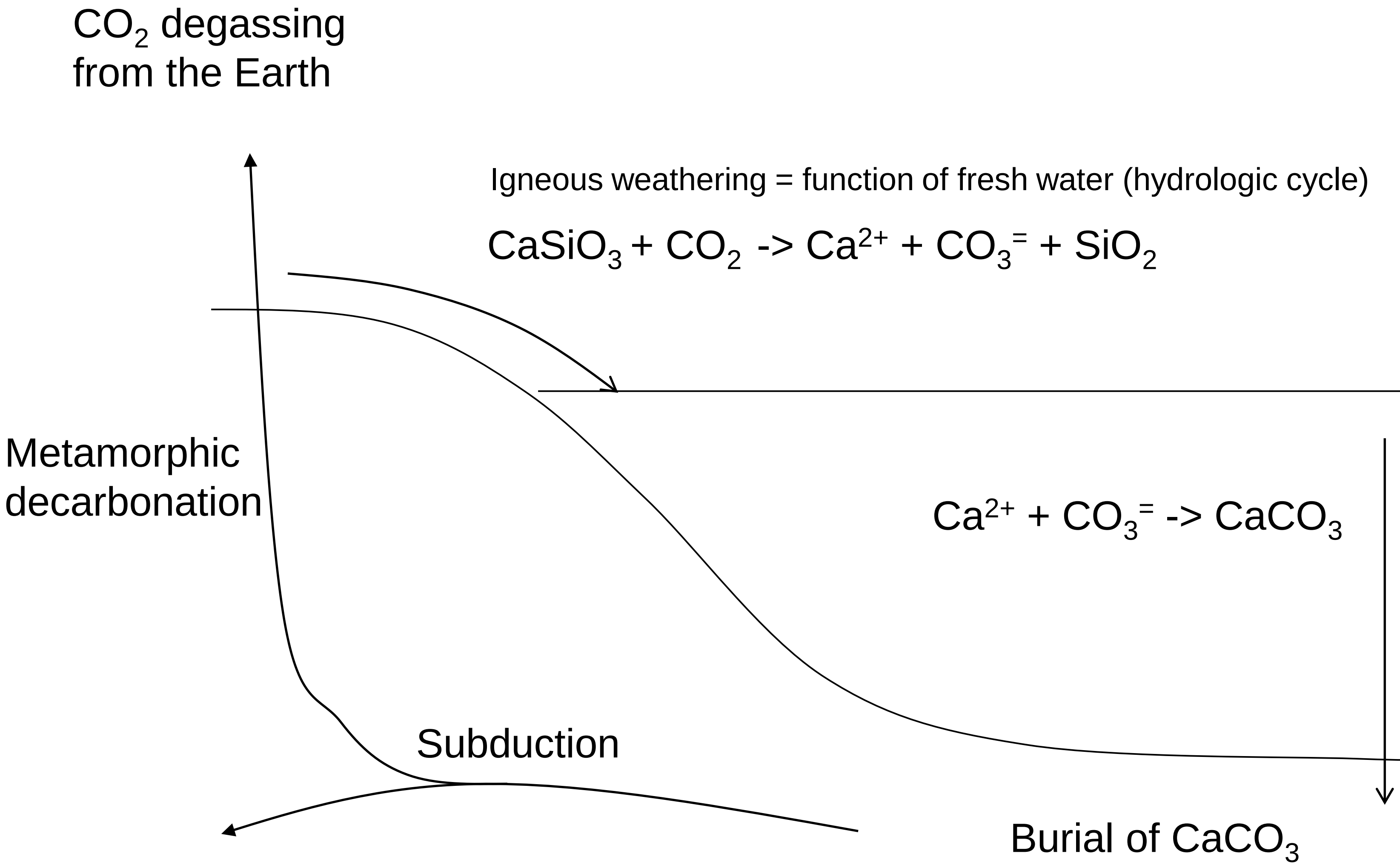
$$CO_2 + CaCO_3 + H_2O \Longrightarrow Ca^{2+} + 2\ HCO_3^-$$



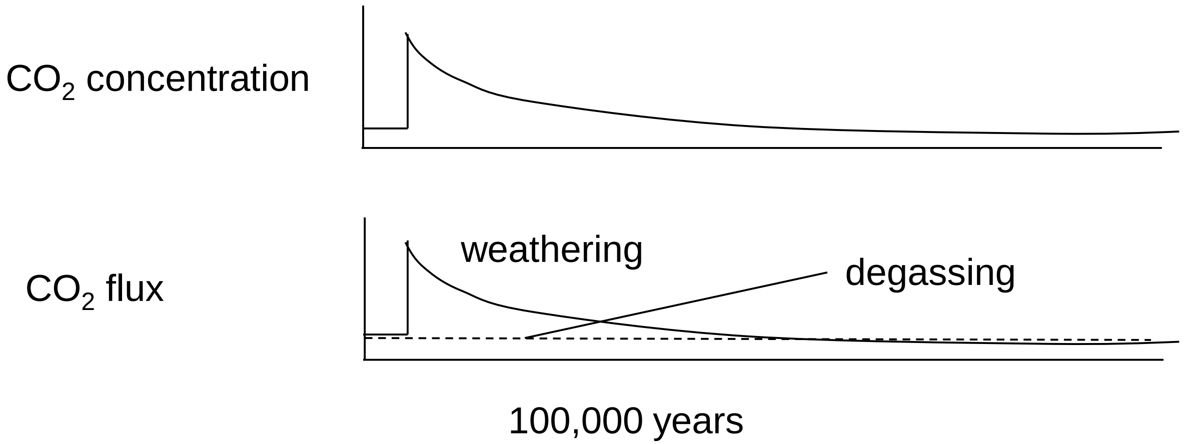
Pulls the airborne fraction
down to ~10%

Time scale = 1000 - 10,000 yrs

Stage III: The CO_2 thermostat from silicate weathering



Stage III: The CO_2 thermostat from silicate weathering

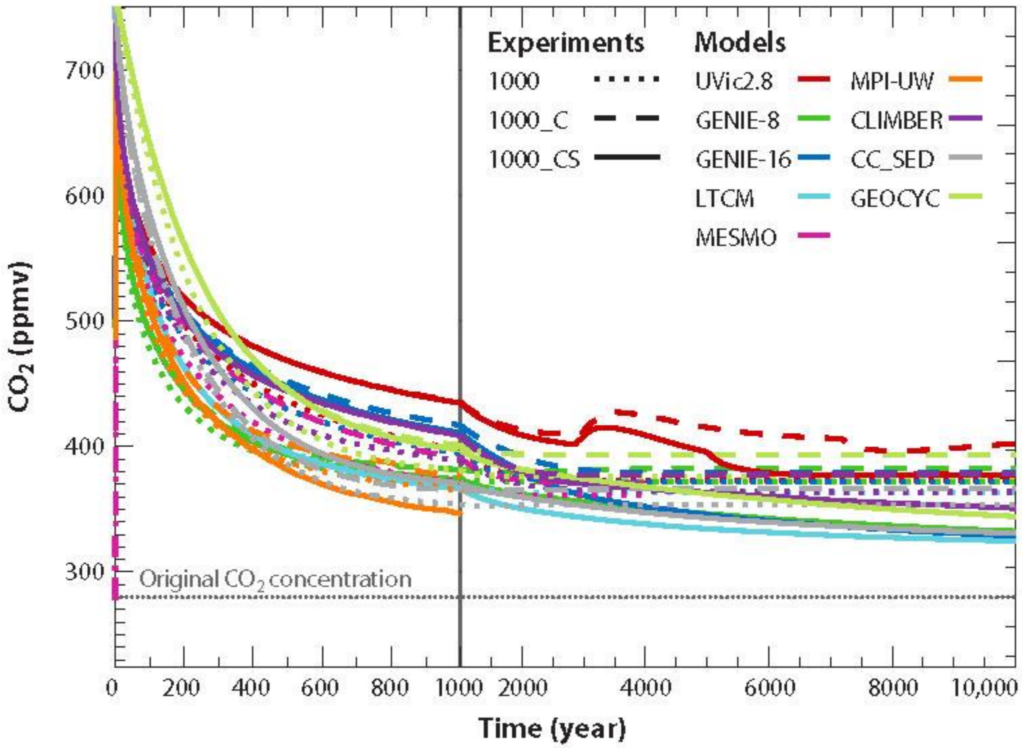


Stabilizes Earth's climate on time scales of ~100,000 years

Helps solve Sagan's "faint young sun" paradox

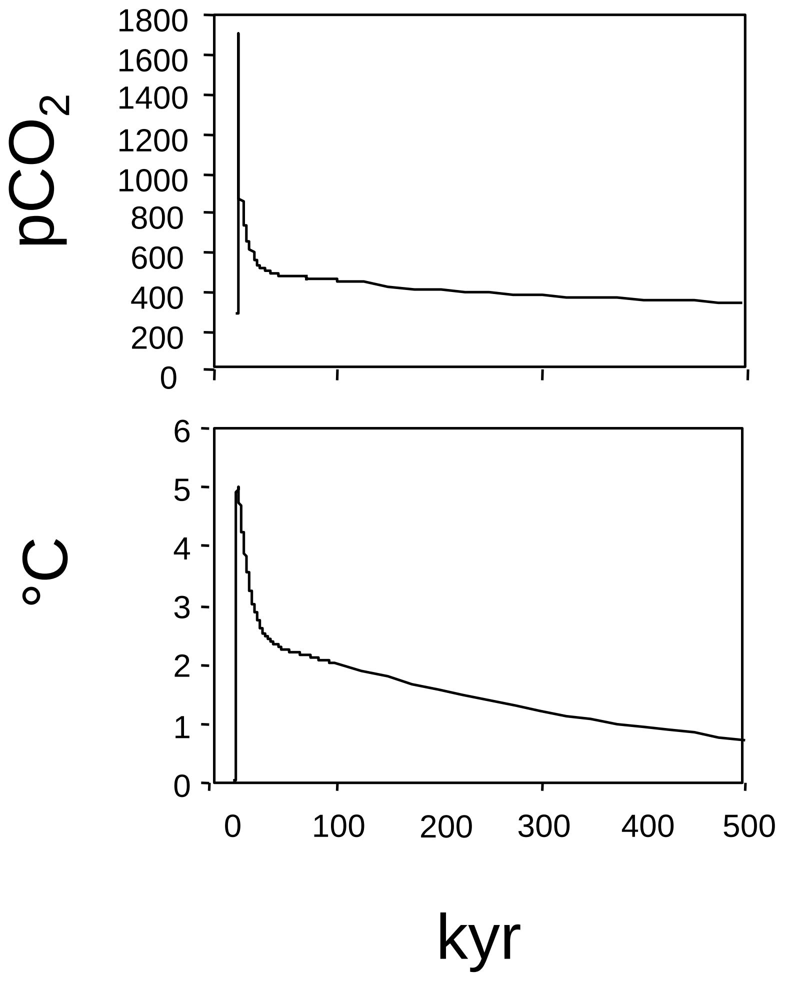
Will determine the longevity of the climate impact from fossil fuel CO_2 release to the atmosphere.

Long Tail Model Intercomparison Project
LTMIP



D. Archer, M.l Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, A. Montenegro, *Ann. Rev. Earth Sciences, 2009*.

Band saturation emphasizes the tail



A geochemical joke

One gallon of gasoline

Usable energy: **2500 kcal**

Unwanted greenhouse energy over CO_2 lifetime:

A geochemical joke

One gallon of gasoline

Usable energy:	**2500 kcal**
Unwanted greenhouse energy over CO_2 lifetime:	**100,000,000,000 kcal**

Hahahaha

SLUGULATOR Methane vs. CO_2

About this model   Other Models

Model Parameters

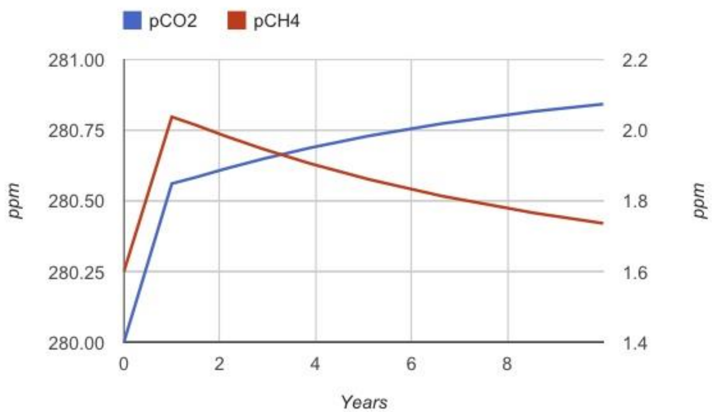
CO_2 spike size	1	Gton C
CH_4 spike size	1	Gton C
Climate sensitivity	3	deg C for doubling CO_2
Efficacy of CH_4 radiative forcing	1.4	

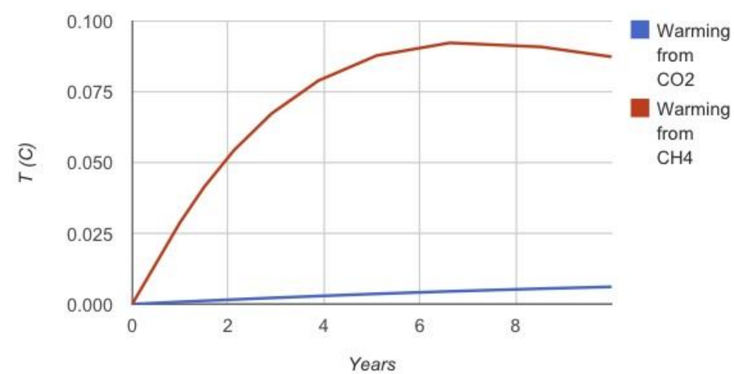
Model Output over 10 years

	Energy Yield From Fossil Fuel 10^{21} Joules	**Energy Trapped** Time Int. Rad. Forc. 10^{21} Joules	**Warming** Time Integrated Deg. C * Years
from CO_2	**0.038**	**2.398**	**0.038**
from CH_4	**0.074**	**41.486**	**0.762**

Concentrations

Surface T. Anomaly





Show 10 years

SLUGULATOR Methane vs. CO_2

About this model   Other Models

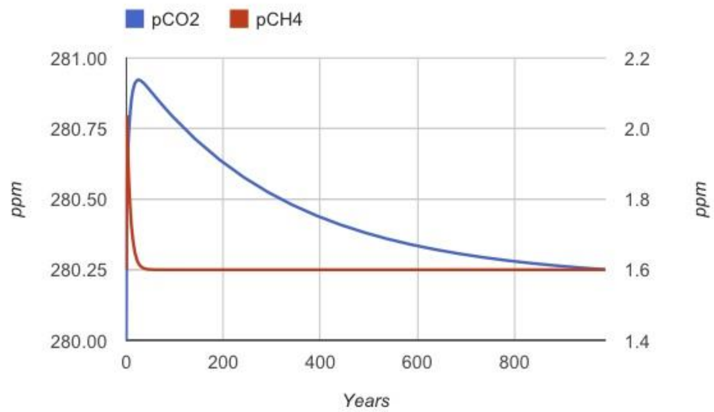
Model Parameters

CO_2 spike size	1	Gton C
CH_4 spike size	1	Gton C
Climate sensitivity	3	deg C for doubling CO_2
Efficacy of CH_4 radiative forcing	1.4	

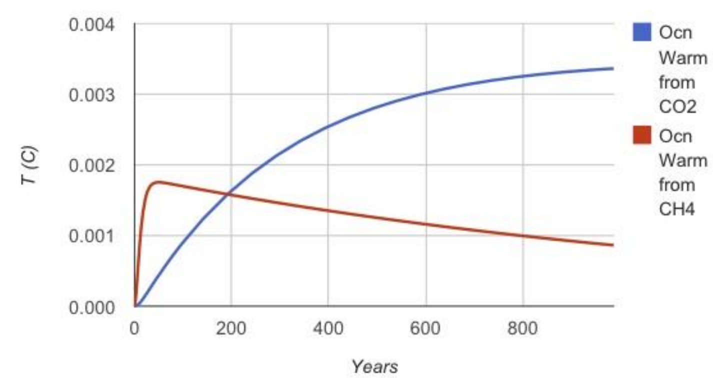
Model Output over 1000 years

	Energy Yield From Fossil Fuel 10^{21} Joules	**Energy Trapped** Time Int. Rad. Forc. 10^{21} Joules	**Warming** Time Integrated Deg. C * Years
from CO_2	**0.038**	**142.765**	**5.035**
from CH_4	**0.074**	**54.969**	**2.104**

Concentrations

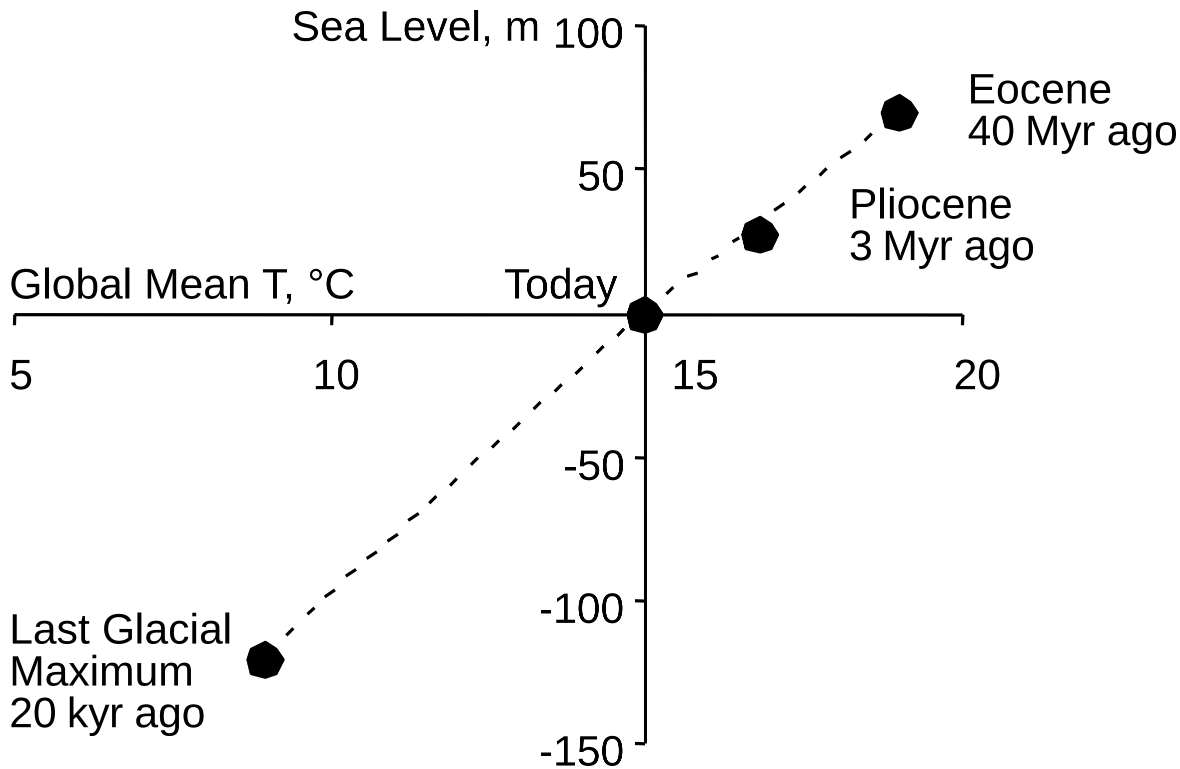


Deep Ocean T. Anomaly



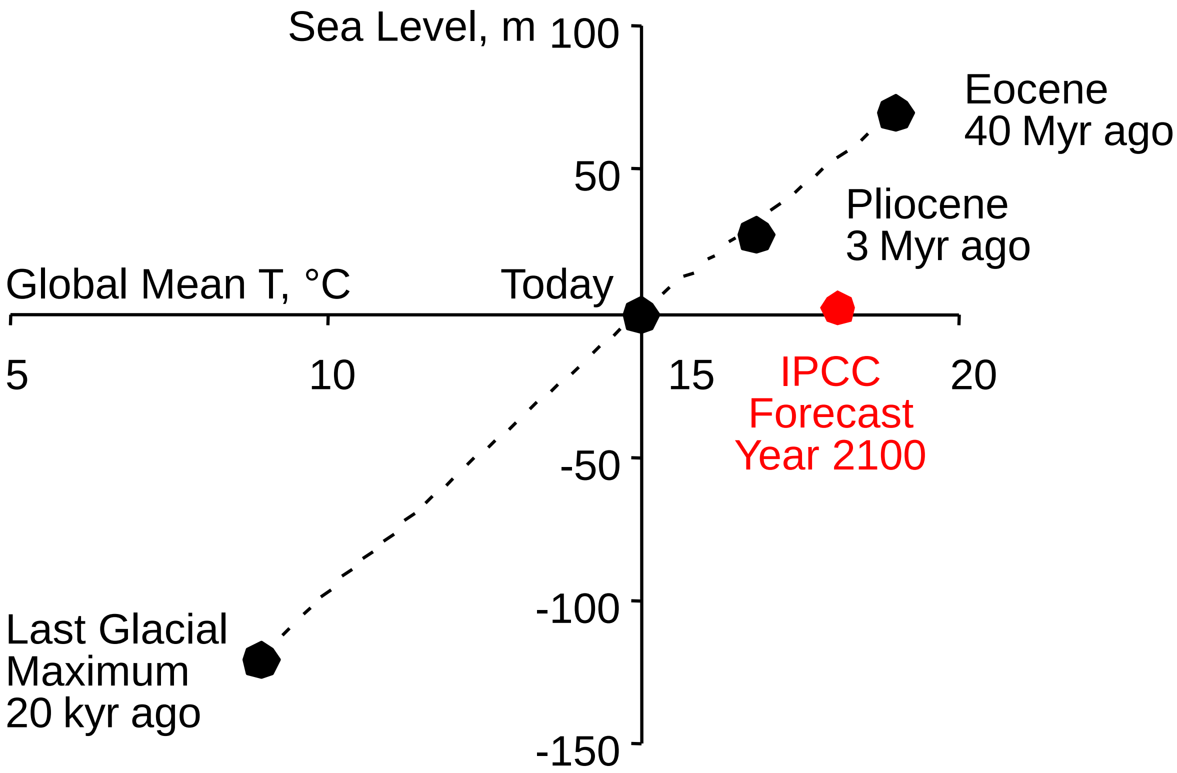
Show 1,000 years

Sea Level



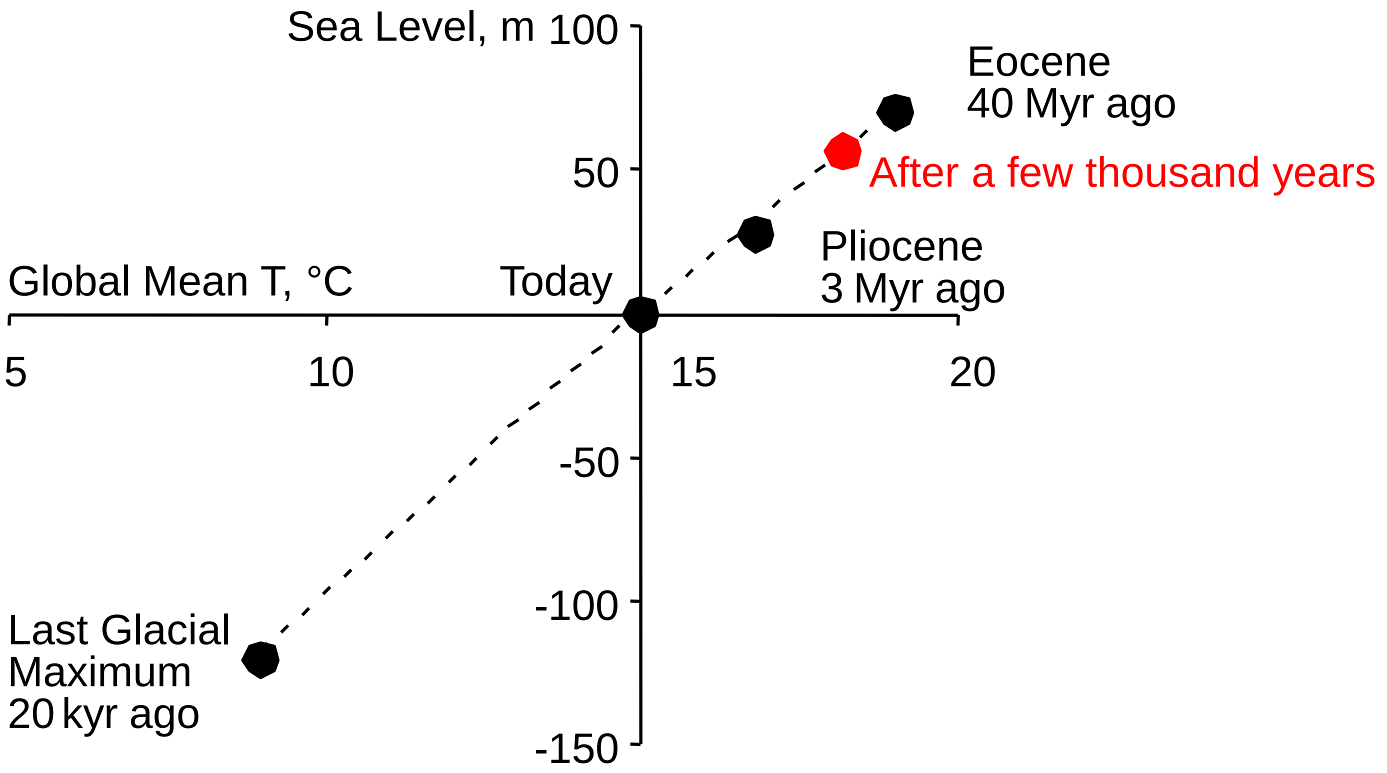
Sea Level, m
100
50
-50
-100
-150
Global Mean T, °C
5
10
15
20
Today
Eocene
40 Myr ago
Pliocene
3 Myr ago
Last Glacial
Maximum
20 kyr ago

Sea Level



Sea Level, m
100
50
-50
-100
-150
Global Mean T, °C
Today
5
10
15
20
Eocene
40 Myr ago
Pliocene
3 Myr ago
IPCC
Forecast
Year 2100
Last Glacial
Maximum
20 kyr ago

Sea Level



Sea Level, m
100
50
-50
-100
-150
Global Mean T, °C
5
10
15
20
Today
Eocene
40 Myr ago
After a few thousand years
Pliocene
3 Myr ago
Last Glacial
Maximum
20 kyr ago

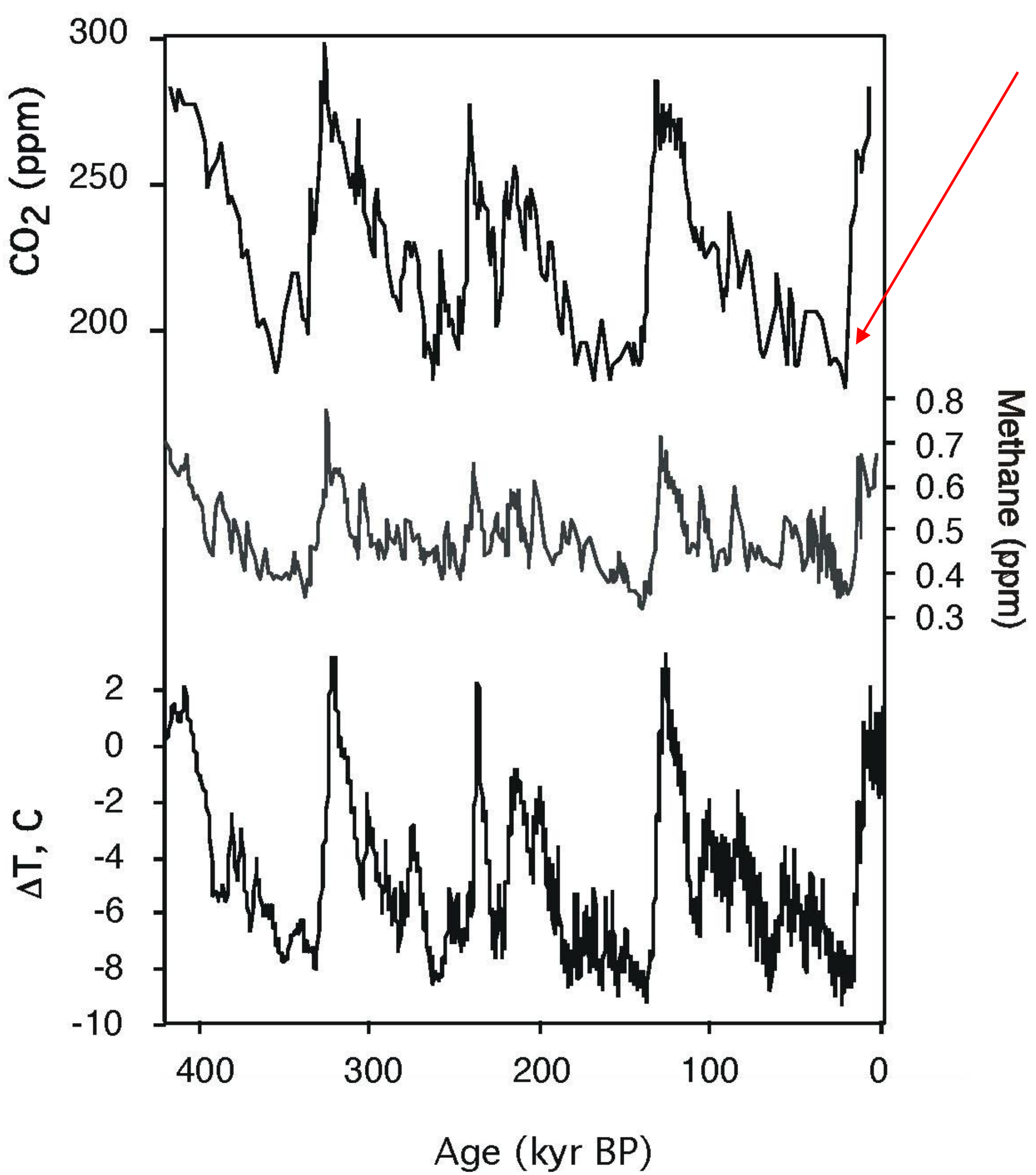
Other Slow Impacts

Melt permafrost (centuries), releasing carbon

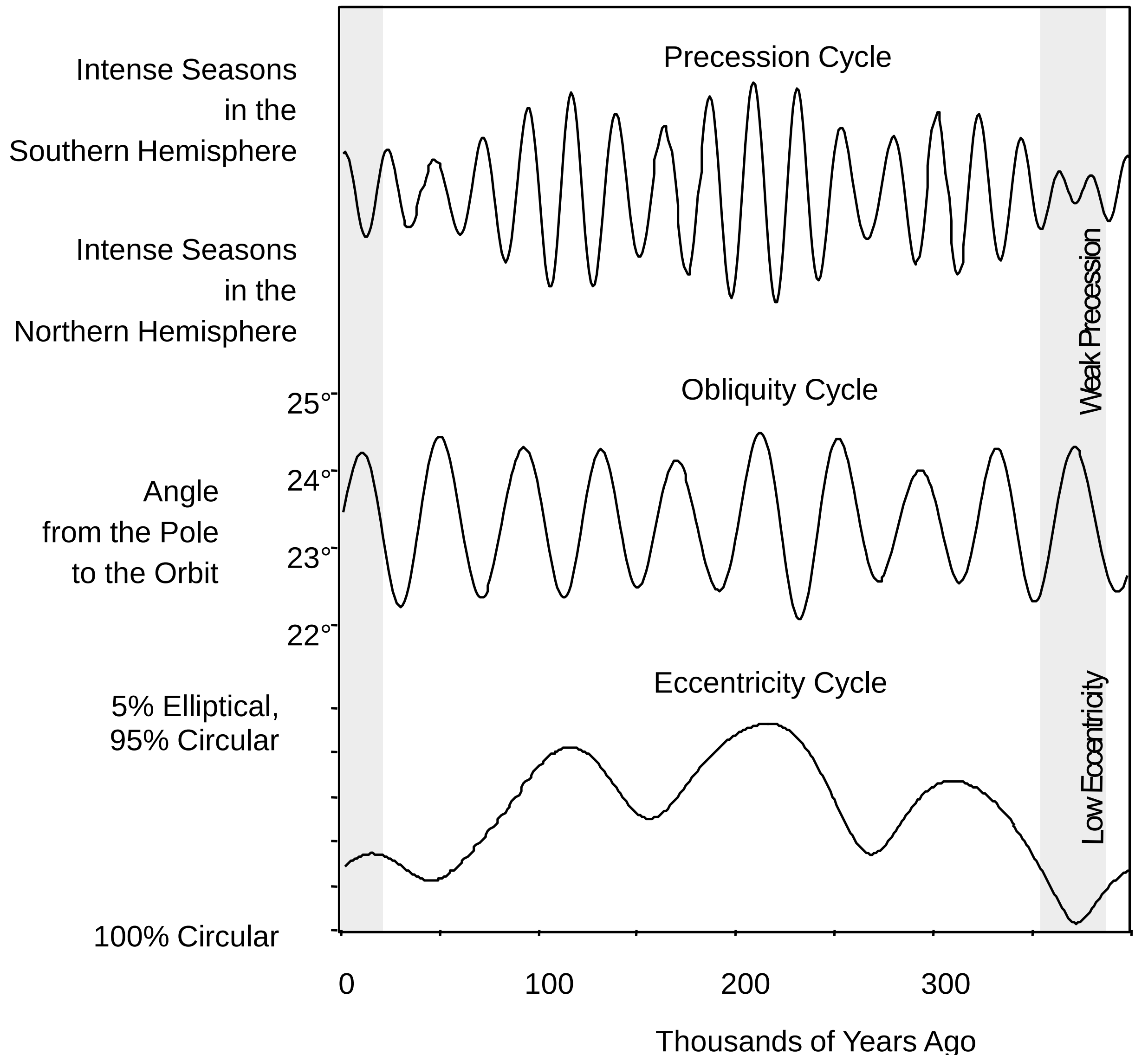
Warm the deep ocean (1000 yrs)

- Thaw methane hydrate
- Decreased O_2 solubility
- Whatever the Glacial / Interglacial CO_2 trick was

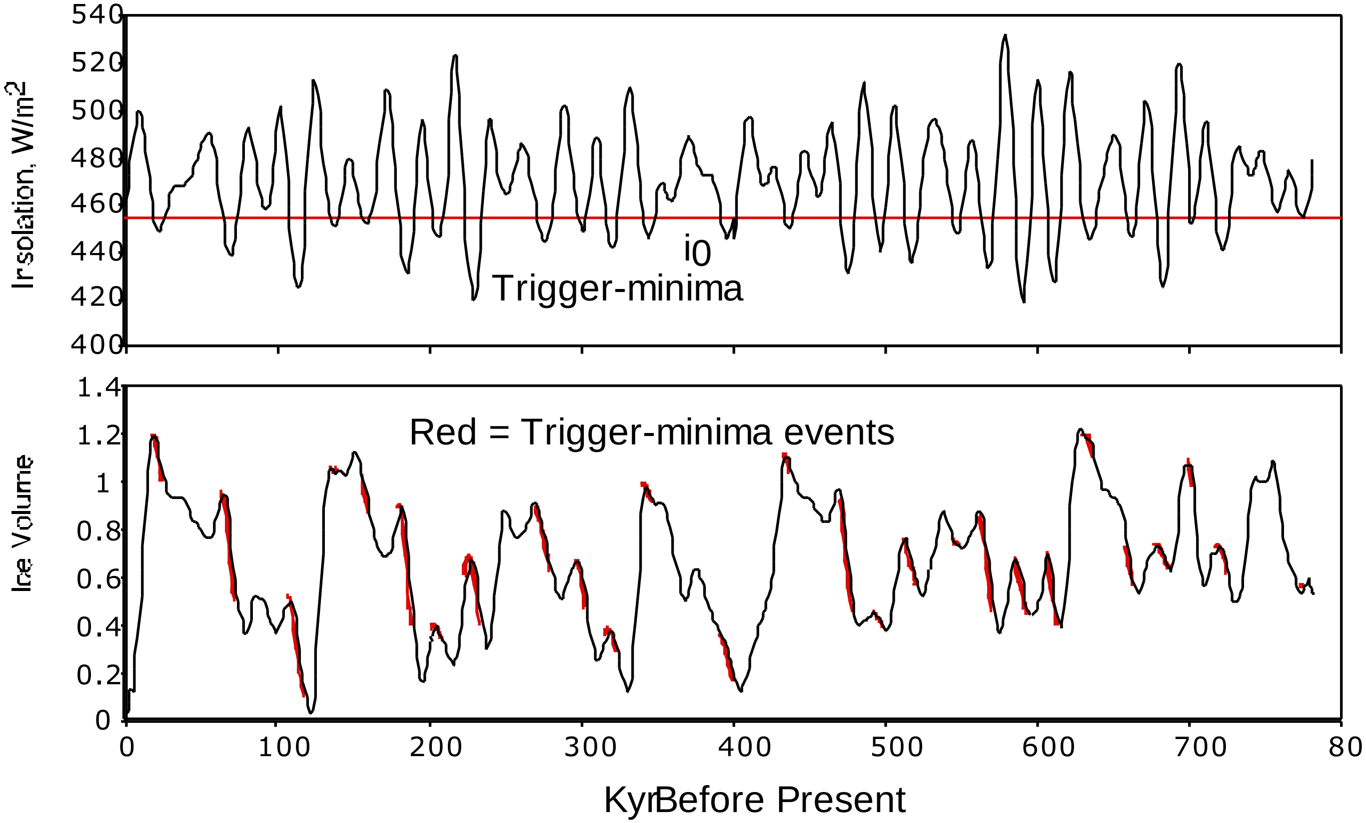
Lower CO_2
During Ice Age



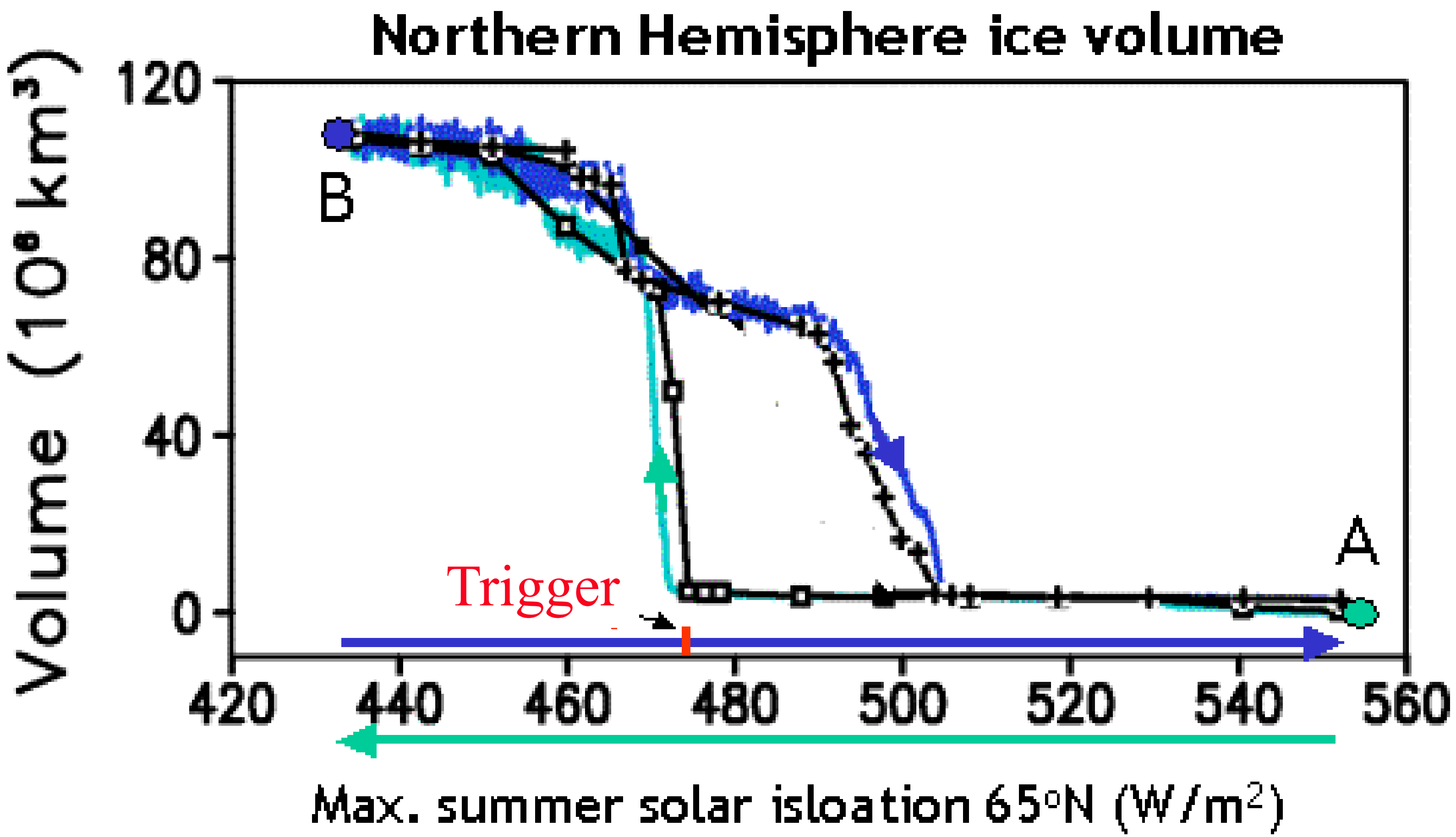
Orbital Forcing of Climate

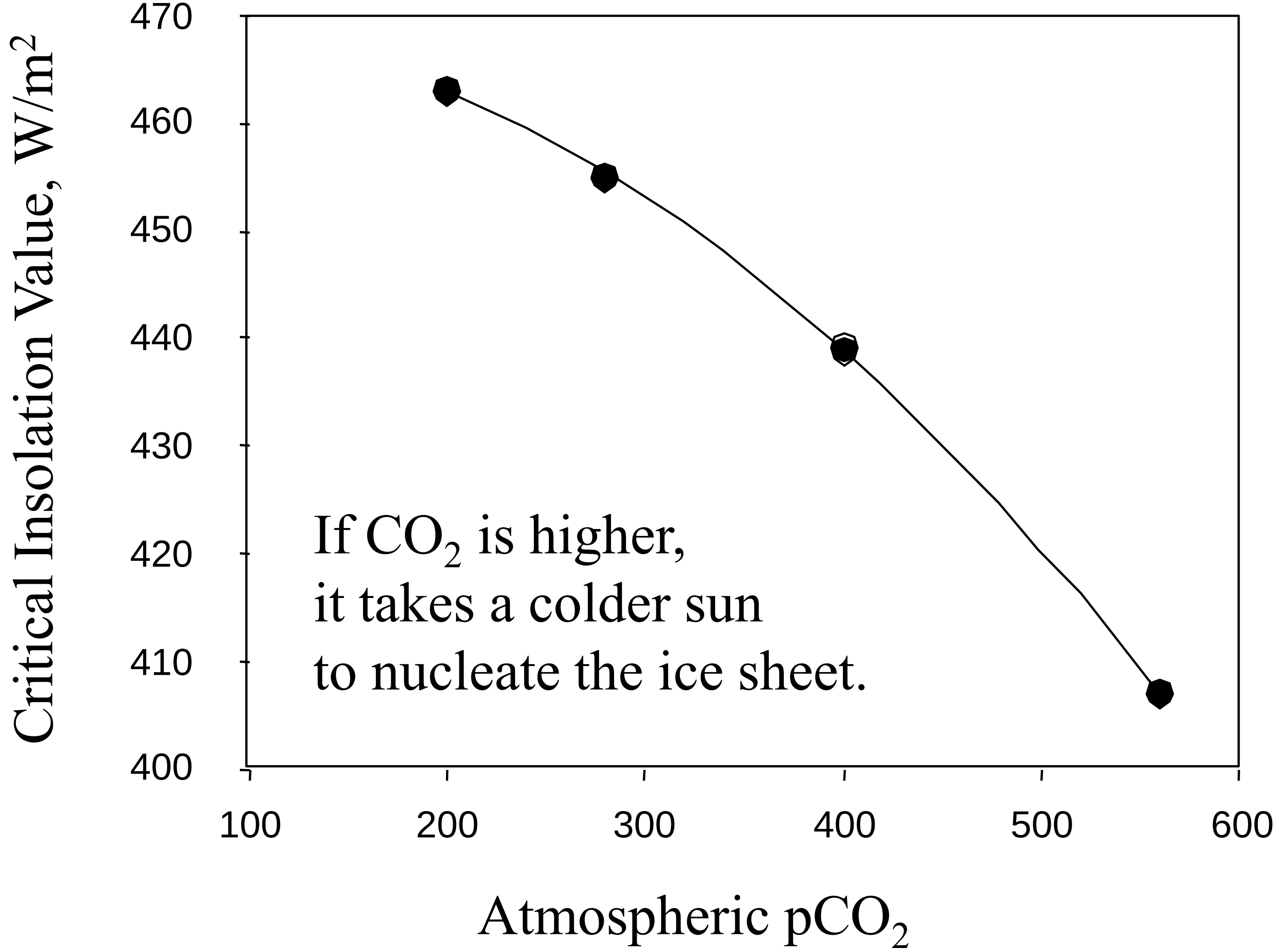


Dim Northern Hemisphere Sun = Growing Ice

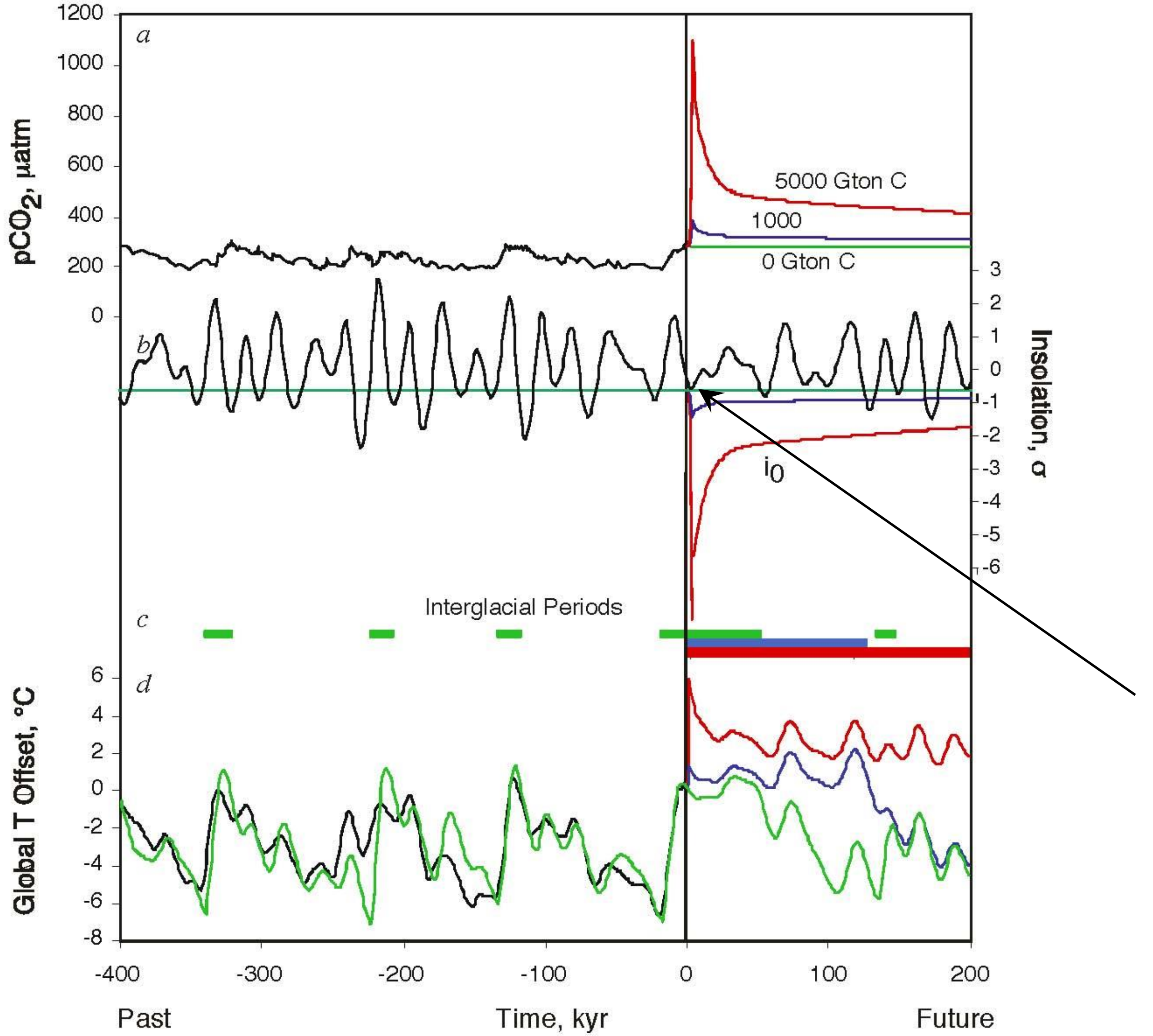


CLIMBER Model Nucleates an Ice Sheet



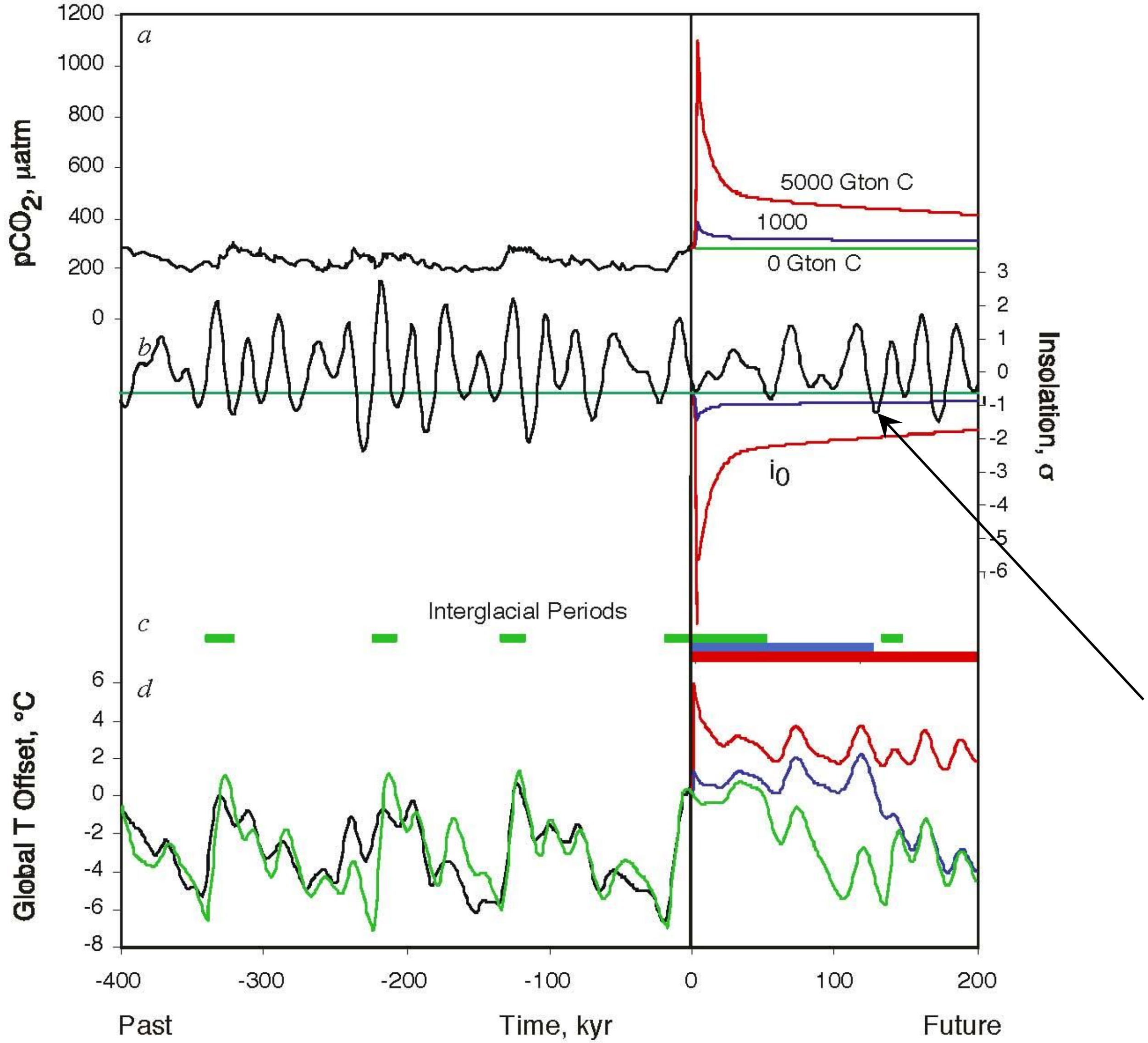


CLIMBER model, Archer and Ganopolski, 2005

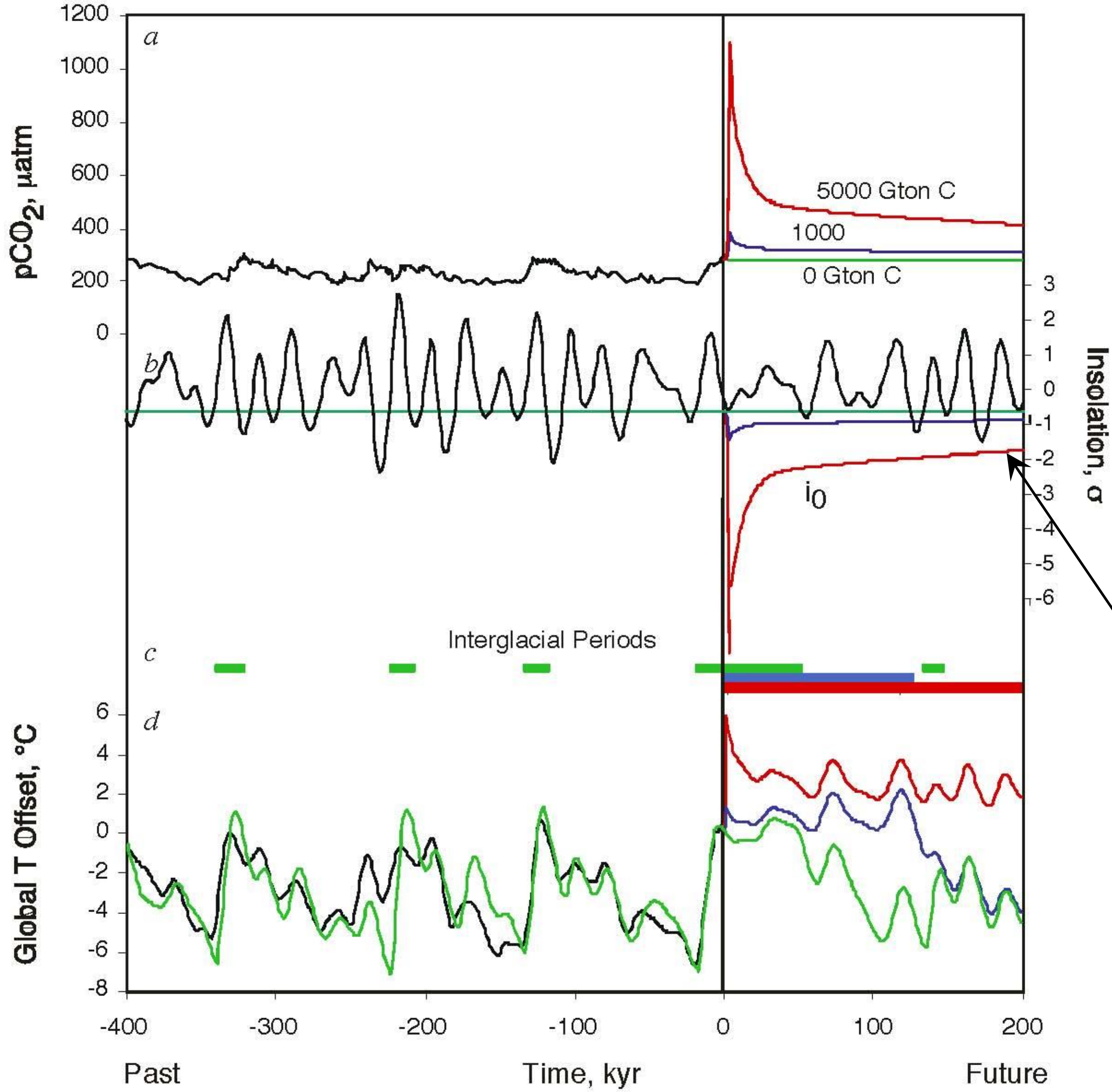


Natural:
Near miss!
Wait until
50 kyr

Archer and Ganopolski, 2005



1000 Gton: Wait until 130 kyr from now



5000 Gton:
No glaciation
for 400 kyr

CO_2 vs. CH_4

CO_2 poses a “trap” for humanity
 now vs. future
 persists essentially forever.

CH_4 we emit will subside within our time
 except for ocean “heat pollution”

CO_2 emissions are the main issue, CH_4 is frosting.

REVIEW

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

S. Pacala[1]* and R. Socolow[2]*

Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century. A portfolio of technologies now exists to meet the world's energy needs over the next 50 years and limit atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration. Every element in this portfolio has passed beyond the laboratory bench and demonstration project; many are already implemented somewhere at full industrial scale. Although no element is a credible candidate for doing the entire job (or even half the job) by itself, the portfolio as a whole is large enough that not every element has to be used.

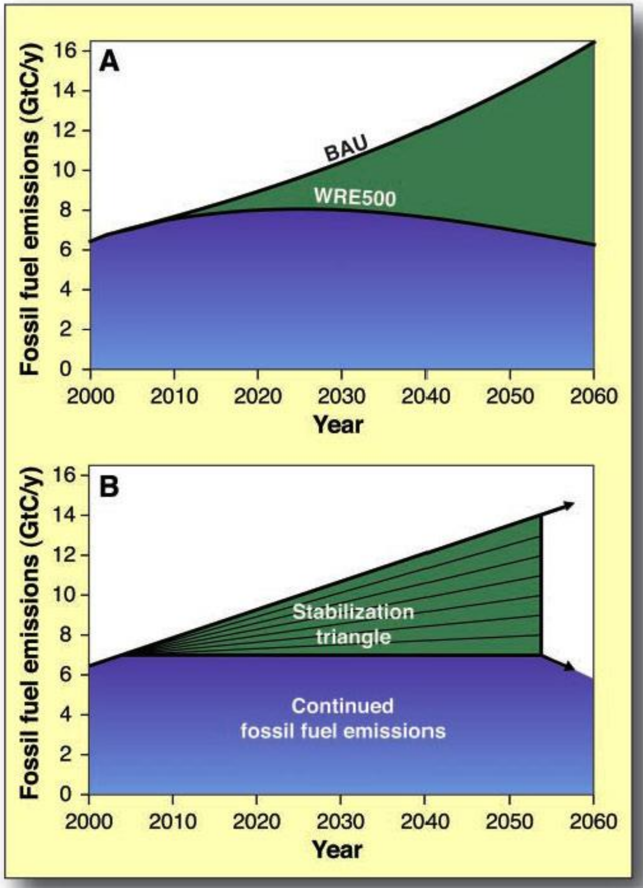


Table 1. Potential wedges: Strategies available to reduce the carbon emission rate in 2054 by 1 GtC/year or to reduce carbon emissions from 2004 to 2054 by 25 GtC.

Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
	Energy efficiency and conservation	
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)	Can be tuned by carbon policy
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year	Urban design, mass transit, telecommuting
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
	Fuel shift	
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)	Competing demands for natural gas
	CO_2 Capture and Storage (CCS)	
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)	H_2 safety, infrastructure
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced without CCS
Geological storage	Create 3500 Sleipners	Durable storage, successful permitting
	Nuclear fission	
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
	Renewable electricity and fuels	
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30×10^6 ha, on land or offshore	Multiple uses of land because windmills are widely spaced
11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2×10^6 ha	PV production cost
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250×10^6 ha (one-sixth of world cropland)	Biodiversity, competing land use
	Forests and agricultural soils	
14. Reduced deforestation, plus reforestation, afforestation, and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
15. Conservation tillage	Apply to all cropland (10 times the current usage)	Reversibility, verification

1 Trillion tons of C => 2 °C peak warming

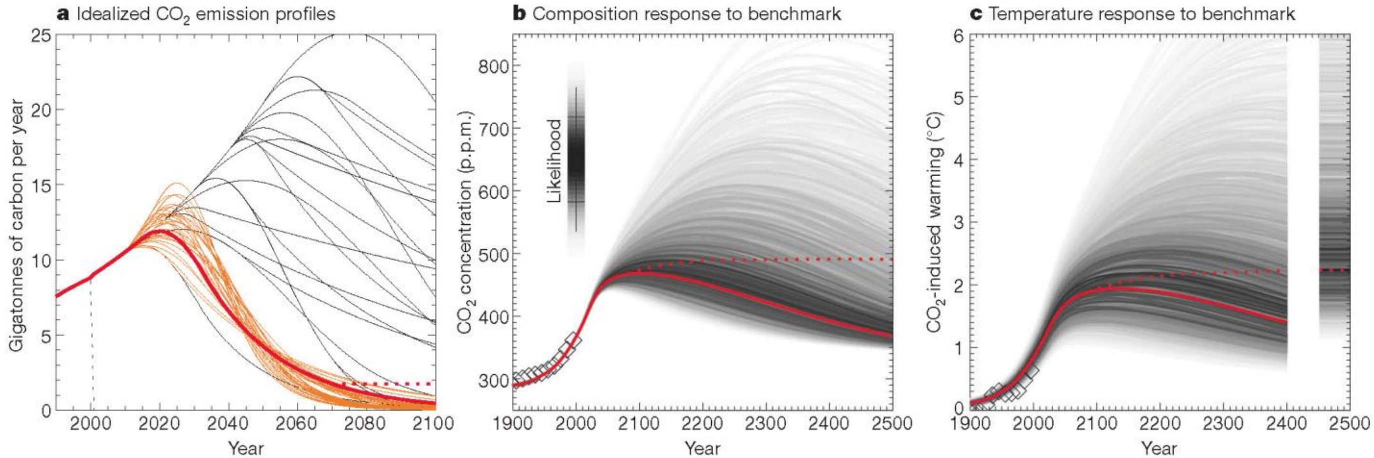
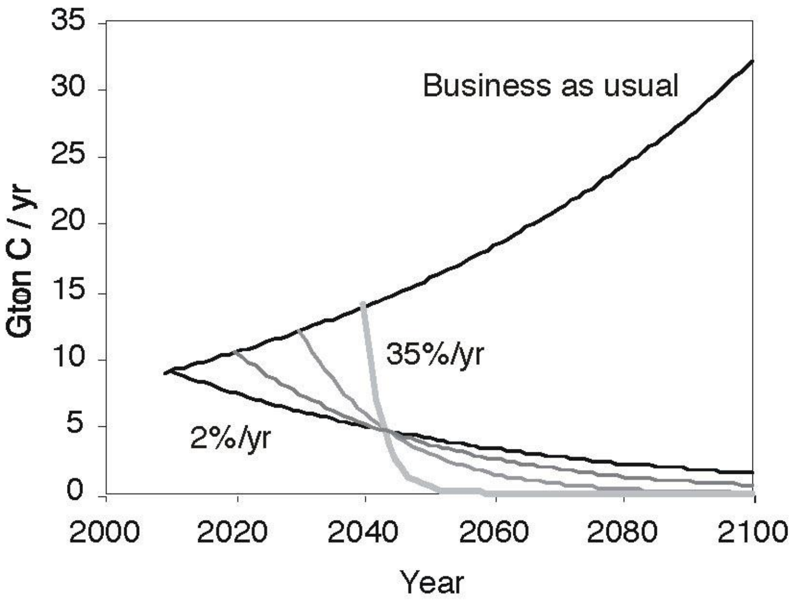


Figure 1 | Idealized carbon dioxide emission scenarios and response to benchmark scenario. **a**, Emissions, including zero emissions after 2000 (dotted black line). Solid red and orange lines show scenarios with cumulative emissions 1750–2500 within 1% of 1 Tt C. Solid red line shows benchmark case and dotted red line shows the '490 p.p.m. stabilization' scenario. **b**, CO_2 concentration response to benchmark scenario with best-fit combination of simple climate model parameters (solid red line) and with random parameter combinations shaded by likelihood (grey plume). The vertical scale bar shows the corresponding likelihood profile for a normally distributed quantity, with black line showing 5–95% (horizontal tickmarks: 17–83%) confidence interval. The dotted red line shows best-fit response to stabilization scenario. **c**, Temperature response to benchmark scenario from simple model: best fit in red and likelihood profile in grey. Bar on right shows likelihood profile for peak warming response to '490 p.p.m. stabilization' emissions scenario: in cases where temperatures are still rising in 2500, equilibrium warming response to 2500 CO_2 concentration is plotted. Diamonds in **b** and **c** show observed CO_2 concentrations and temperatures (relative to 1900–1920), respectively.

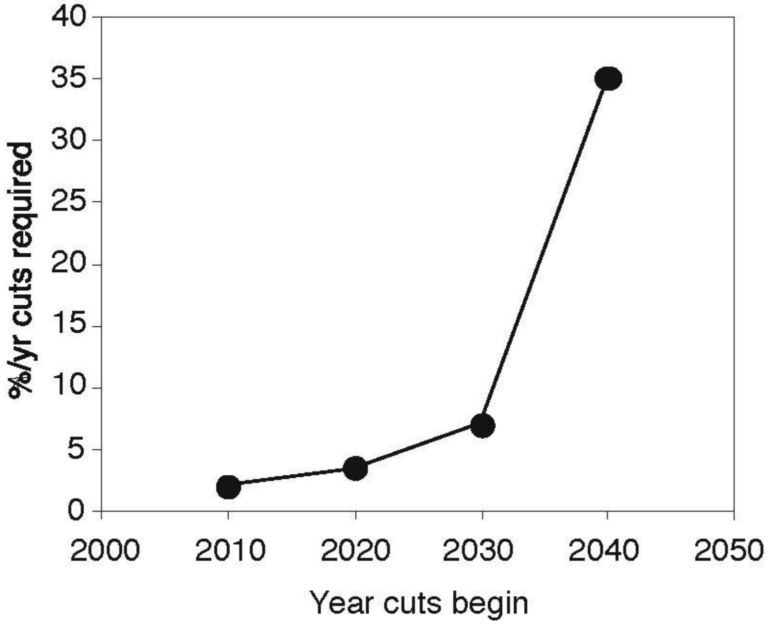
Allen et al 2009



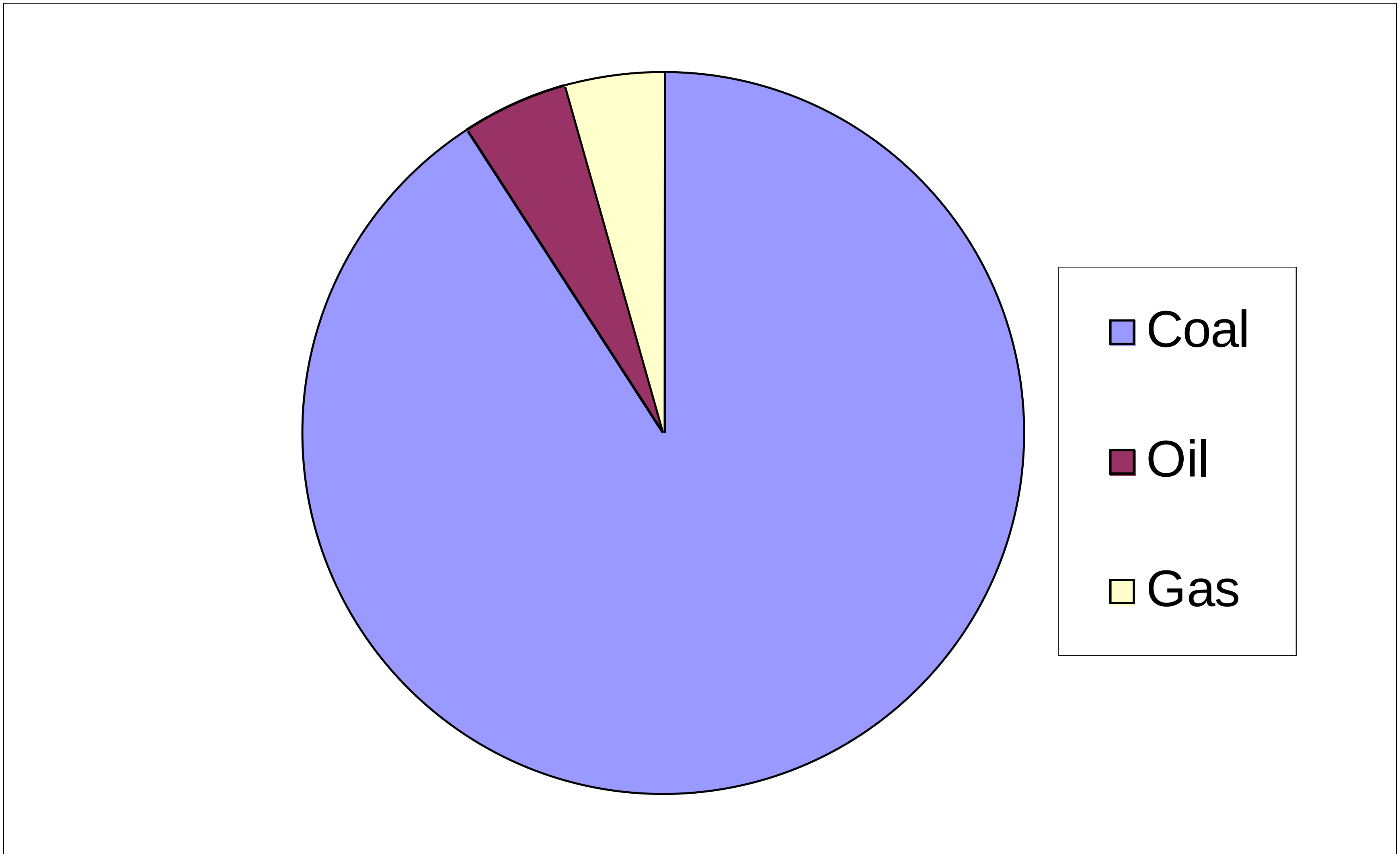
1 Trillion tons of C

Already released: 1/2 trillion tons
0.3 from fuels
0.2 from deforestation

Costs (cuts / year) go up if we wait



Fossil fuels are mostly coal



Conclusions

The impacts of global warming will last for millennia (not just a few centuries).

Lesson from the past: Sea level is 100x more sensitive to Earth's temperature on thousand-plus year timescales than the forecast for the year 2100.

Forget methane: Keep your eye on the ball, which is CO_2