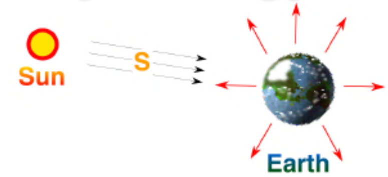
Carbon-Climate Interaction and The Long Tail of CO_2

Please read (from class website):

- Gregory et al (2009). Quantifying carbon cycle feedbacks. *Jour. Climate* 22: 5232-5250.
- Archer and Brovkin (2008). Millennial atmospheric lifetime of anthropogenic CO_2. *Climatic Change* 90:283-297.

Planetary Energy Balance



Energy In = Energy Out

$$S(1-\alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^{\circ}\mathrm{C}$$

But the observed T_s is about 15° C

Earth's Climate as a "Black Box"

$F = \dfrac{S_0(1-\alpha)}{4}$

240 W m^{-2} → **Climate System** → 15 °C

T_S

Absorbed Sunshine In

Surface Temperature Out

Climate Forcing, Response, and Sensitivity

ΔF

+ 1 W m^{-2} → **Climate System** → ? °C

ΔT_S

Forcing (change in absorbed sunshine)

Response: (Change in Surface Temperature)

Climate Forcing, Response, and Sensitivity

Forcing (change in sunshine)

ΔF + 1 W m^{-2} → **Climate System** → ΔT_S ? °C

Response: (Change in Surface Temperature)

"Let's do the math ..."

$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T^4$$

$$T = \left[\frac{S_0(1-\alpha)}{4\sigma}\right]^{1/4} = (F/\sigma)^{1/4}$$

A 1 W m^{-2} change in absorbed sunshine produces about a 0.26 °C change in planet's temperature

Baseline Climate Sensitivity

"Let's do the math ..."

$$S_0(1-\alpha)\pi r^2 = 4\pi r^2 \sigma T^4$$

$$S_0(1-\alpha) = 4\sigma T^4$$

$$F = \frac{S_0(1-\alpha)}{4} = \sigma T^4$$

$$\frac{dF}{dT} = 4\sigma T^3 \equiv \lambda_{BB}$$

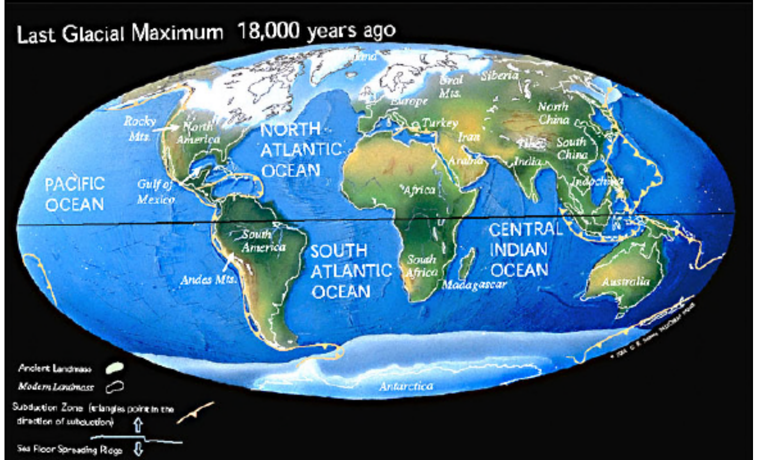
$$\lambda_{\mathrm{BB}} = 4\sigma_{\mathrm{SB}}\, 255^3 = 3.8 \ \mathrm{W\ m^{-2}\ K^{-1}}$$

Total Climate Sensitivity

$$F_{2\times} = 3.7 \ \mathrm{W\ m^{-2}} \qquad T_{2\times} = \frac{F_{2\times}}{\lambda}.$$

- Radiative forcing is 3.7 W m^{-2} per doubling of CO_2 (based on spectroscopy & RT modeling)
- "Baseline" sensitivity λ_{BB}=3.8 W m^{-2} K^{-1}, so only about 1 K warming per 2 x CO_2
- But total sensitivity depends on the magnitude of climate feedback λ

Learning from the Past



Estimating Total Climate Sensitivity

- At the Last Glacial Maximum (~ 18k years ago) surface temp ~ 5 K colder
- CO_2 was ~ 180 ppm (weaker greenhouse, 3.7 W m^{-2} more OLR)
- Brighter surface due to snow and ice, therefore 3.4 W m^{-2} more reflected solar

$$\frac{\Delta T_S}{\Delta F} = \frac{T_S(now) - T_S(then)}{F(now) - F(then)}$$

$$= \frac{5K}{(3.7 + 3.4)Wm^{-2}} = 0.70\frac{K}{Wm^{-2}}$$

Almost 3x as sensitive as suggested by Stefan-Boltzmann alone …
Other feedbacks must be going on as well

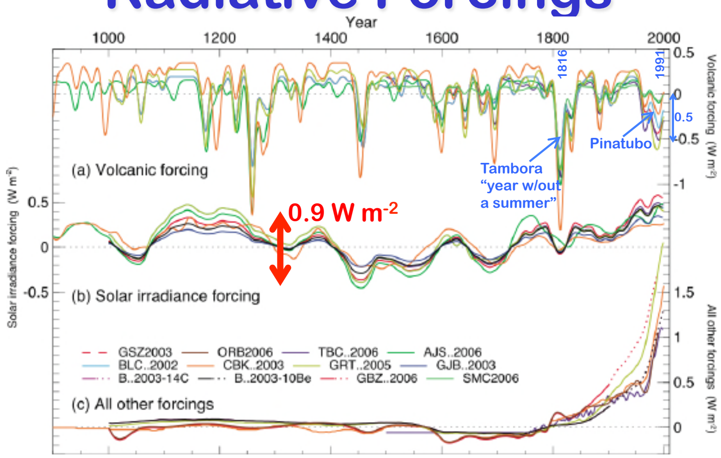
Deglaciation Analog

- Warming after last glacial maximum ~ 5 K
- Climate forcing ~ 7 W m^{-2}
- Total climate sensitivity (including feedback) about 1.42 K (W m^{-2})$^{-1}$

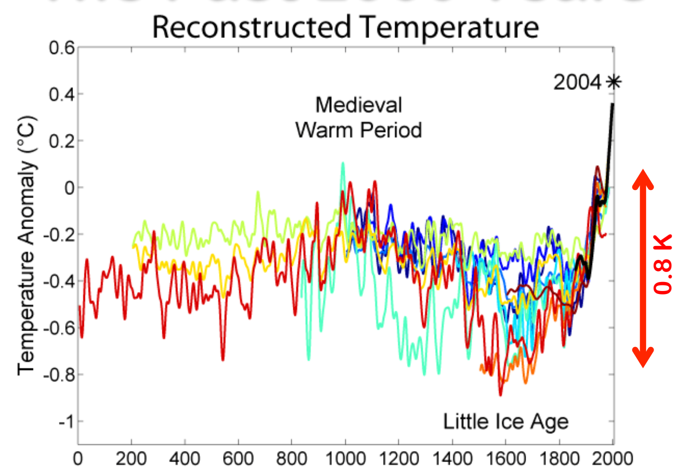
$$\lambda \equiv \frac{\Delta F}{\Delta T} = \frac{1}{0.7\ K/(Wm^{-2})} = 1.4\,Wm^{-2}\ K^{-1}$$

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda} = \frac{3.7\,Wm^{-2}}{1.4\,Wm^{-2}\ K^{-1}} = 2.6K$$

Reconstructed Radiative Forcings



The Past 2000 Years



http://commons.wikimedia.org/wiki/File:2000_Year_Temperature_Comparison.png

Second Millennium Analog

- Cooling from Medieval Warm Period to Little Ice Age ~ 0.8 K
- Solar forcing ~ 0.9 W m^{-2} (somewhat complicated by volcanic forcing)

A frost fair on the Thames at Temple Stairs, c 1684. Abraham Hondius Museum of London

Total climate sensitivity (including feedback)

λ ~ 1.1 K (W m^{-2})$^{-1}$

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda} = \frac{3.7\,Wm^{-2}}{1.1\,Wm^{-2}\ K^{-1}} = 3.4K$$

Volcanic Analog

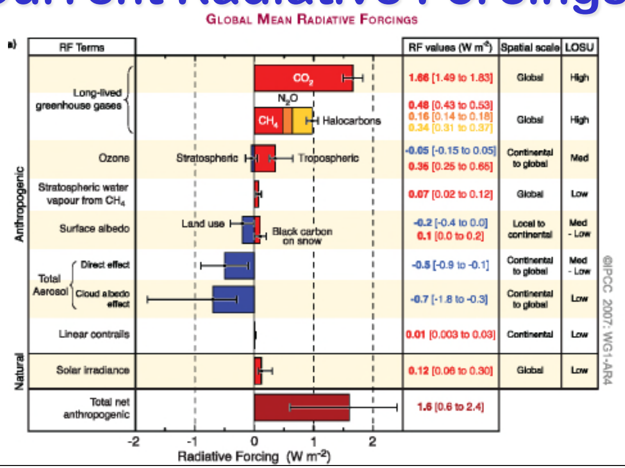
- Cooling following eruption of Mount Pinatubo in 1991 ~ 0.6 K
- Volcanic forcing ~ 0.5 W m^{-2}
- Total climate sensitivity (including only "fast" feedback)

Total climate sensitivity (including feedback)

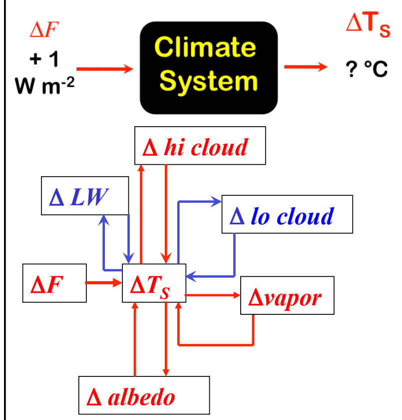
λ ~ 1.2 K (W m^{-2})$^{-1}$

$$\Delta T_{2x} = \frac{\Delta F_{2x}}{\lambda} = \frac{3.7\,Wm^{-2}}{1.2\,Wm^{-2}\ K^{-1}} = 3.1K$$

Comparison of Current Radiative Forcings



Climate Feedback Processes



- **Positive Feedbacks (amplify changes)**
  - Water vapor
  - Ice-albedo
  - High clouds
- **Negative feedbacks (damp changes)**
  - Longwave cooling
  - Low clouds

$$F = \lambda T = T(\lambda_{BB} + \lambda_{albedo} + \lambda_{vapor} + \lambda_{cloud} + \ldots)$$

Climate Feedback

$$F = \lambda T = T(\lambda_{BB} + \lambda_{albedo} + \lambda_{vapor} + \lambda_{cloud} + \ldots)$$

$$\lambda_{\mathrm{BB}} T = F + \sum_{i \neq \mathrm{BB}} (-\lambda_i T)$$

- Feedback processes are additive
- Each process can be seen as adding to or subtracting from the "original" forcing
- $\lambda < 0$ is a "positive feedback" (adds to F)
- $\lambda > 0$ is a "negative feedback" (subtracts from F)

"Climate Gain"

$$\lambda_0 T = F + \sum_{i>0} y_i T \Rightarrow F = T(\lambda_0 - y),$$

$$y = \sum_{i>0} y_i = -\sum_{i>0} \lambda_i,$$

- y is a combined feedback parameter, with sign opposite of λ

$$T = \frac{F}{\lambda_0 - y} = \frac{F/\lambda_0}{1 - y/\lambda_0}.$$

$$T = G_T T_0 \quad G_T = \frac{1}{1 - g_T} \quad g_T \equiv \frac{y}{\lambda_0} = \sum_{i>0} \frac{y_i}{\lambda_0} = \sum_{i>0} \frac{(-\lambda_i)}{\lambda_0}$$

- G_T is the "gain" after feedbacks take effect

Climate Sensitivity:
Forcing, Feedback, and Response

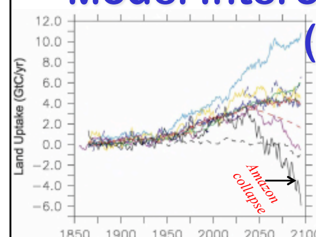
$$T = T_0 \sum_{j=0}^{\infty} g_T^j = \frac{T_0}{1 - g_T} = G_T T_0.$$

- *Eventual* response is amplified (or damped) by the gain factor G_T
- Response may be slow because of thermal inertia (heat capacity and slow transport) associated with oceans and ice sheets

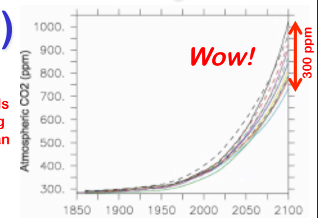
$$F = \rho T \quad \rho = \lambda + \kappa = \sum \lambda_i + \kappa,$$

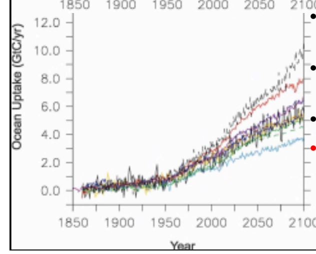
- ρ combines feedback and inertia at a particular time during warming

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)

Carbon-Climate Interactions

atmos CO_2

land carbon

ocean carbon

emitted carbon $\rightarrow$ $C_E = C + C_L + C_O$

$C = C_{atm} - C_I$

Carbon (biogeochemical, β) effect

$C_\beta = C_{L\beta} + C_{O\beta}$

mostly from CO_2 fertilization

mostly from enhanced air-sea gas exchange

Climate (γ) effect

$C_\gamma = C_{L\gamma} + C_{O\gamma}$

mostly from enhanced respiration

mostly from enhanced thermal stratification

Carbon-Climate Interactions

$$C_E = C + C_\beta + C_\gamma$$

$C_\beta = \beta C$, β (GtC GtC^{-1})

$C_\gamma = \gamma T$, γ (GtC K^{-1})

$$C_E = C + \beta C + \gamma T$$

- **Separate simulations** to quantify biogeochemical and climate effects
- Subtract simulated atmospheric CO_2 from initial condition (C_1) to calculate C
- **Calculate β and γ from simulated C_L and C_O**

Carbon-Climate Forcing and Feedback

Climate Forcing at time when (CO_2 – preindustrial) = C

$$F_C(C) = F_{2\times}\frac{\ln[(C_1 + C)/C_1]}{\ln 2} \simeq \phi C.$$

When CO_2 = 2 x C_1, $\phi = F_{2x} / C \sim 3.7$ W m^{-2} / (600 GtC)
(simple linearization of climate forcing)

$$C_E = uC \quad u = \sum_i u_i = 1 + \beta + u_\gamma$$

"Airborne fraction" of total CO_2 emissions depends on both β and γ

$$A = \frac{C}{C_E} = \frac{1}{u} = \frac{1}{\sum u_i} = \frac{1}{1 + \beta + \phi\gamma/\rho}.$$

"Carbon-Climate Gain"

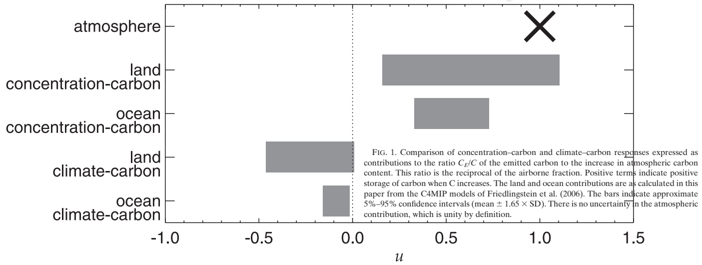
"Airborne fraction" of total CO_2 emissions depends on both β and γ

$$A = \frac{C}{C_E} = \frac{1}{u} = \frac{1}{\sum u_i} = \frac{1}{1 + \beta + \phi\gamma/\rho}.$$

$$C = AC_E, \quad A = \frac{1}{1 - g_C} \qquad g_C = -\sum_{i>0} u_i = -\beta - u_\gamma.$$

- Carbon gain is defined in such a way as to be exactly analogous to climate gain
- Two components:
  - Concentration-carbon feedback β
  - Climate-carbon feedback γ

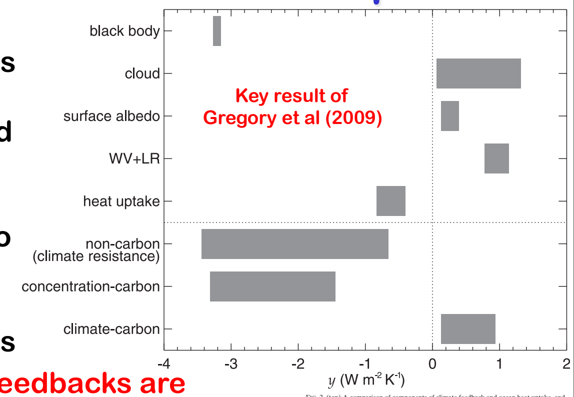
Carbon-Climate Responses



- Derived by Gregory et al (2009) from C4MIP model output (Friedlingstein et al, 2006)
- -u for CO_2 is analogous to $-\lambda$ for temperature
- Concentration-climate feedback is stronger, negative, and most uncertain (esp for land)

Climate Feedback Comparison

- Carbon feedbacks are compared "apples-and-apples" to other climate feedbacks



- Carbon feedbacks are strongest and most uncertain of all feedback processes in climate system

Nitrogen Limitation

Biogeosciences, 6, 2099–2120, 2009
www.biogeosciences.net/6/2099/2009/

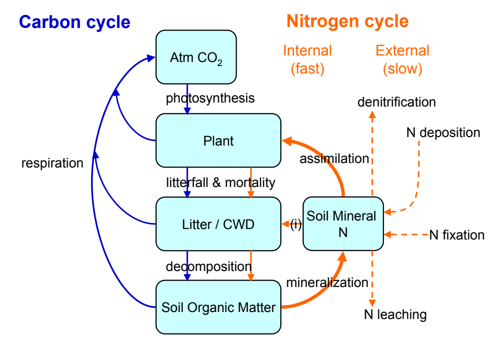
Biogeosciences

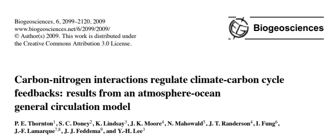
Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model

P. E. Thornton[1], S. C. Doney[2], K. Lindsay[3], J. K. Moore[4], N. Mahowald[5], J. T. Randerson[4], I. Fung[6], J.-F. Lamarque[7,8], J. J. Feddema[9], and Y.-H. Lee[3]

- Recall that many FACE studies find transient response of NPP to CO_2 enrichment which fades after a few years
- Will nutrient limitation minimize CO_2 fertilization and carbon-concentration feedback, ultimately meaning extreme sensitivity to climate change?

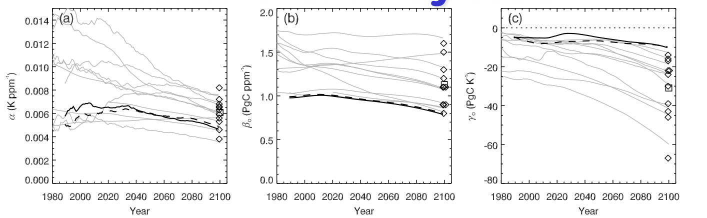
Carbon-Nitrogen Interactions



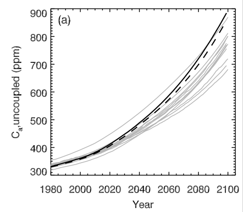


- Plant growth limited by available mineral nitrogen
- Mineralization of organic N is faster at higher temperatures
- N deposition and fixation can help

Coupled Climate with C & N Cycles



- Dramatically lower β because N limitation reduces influence of CO_2 fertilization
- Smaller (negative) γ because of enhanced N mineralization
- Higher airborne fraction of CO_2



CMIP5 Carbon Feedbacks

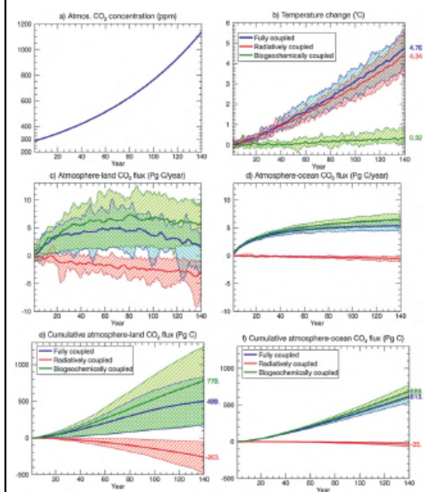


FIG. 1. (a) Atmospheric CO_2 concentration (ppm) used in the 1% increasing CO_2 simulations. (b) Model mean values and the range across the nine participating models for simulated temperature change, compared to the control simulation, (c) atmosphere–land and (d) atmosphere–ocean CO_2 fluxes, and (e),(f) their cumulative values, from the fully, radiatively, and biogeochemically coupled simulations.

- Results from latest IPCC (AR5) still show enormous spread of β and γ
- Concentration-Carbon dominates

VOLUME 26 JOURNAL OF CLIMATE 1 AUGUST 2013

Carbon–Concentration and Carbon–Climate Feedbacks in CMIP5 Earth System Models

VIVEK K. ARORA,[a] GEORGE J. BOER,[a] PIERRE FRIEDLINGSTEIN,[b] MICHAEL EBY,[c] CHRIS D. JONES,[d] JAMES R. CHRISTIAN,[a] GORDON BONAN,[e] LAURENT BOPP,[f] VICTOR BROVKIN,[g] PATRICIA CADULE,[f] TOMOHIRO HAJIMA,[h] TATIANA ILYINA,[g] KEITH LINDSAY,[e] JERRY F. TJIPUTRA,[i] AND TONGWEN WU[j]

CMIP5 Carbon Feedback

- Land β and γ each vary by a factor of 6 !
- Oceans vary too, but over a much smaller range
- Dominant source of uncertainty

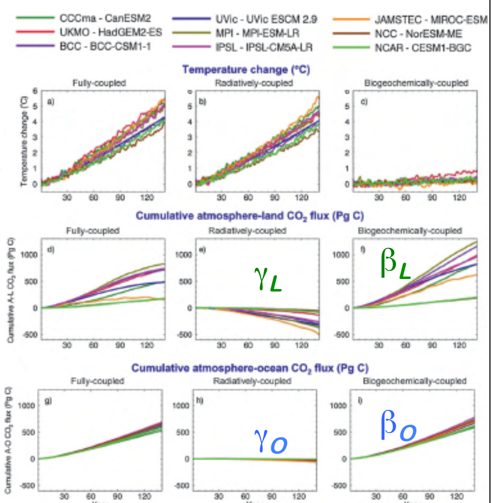


FIG. 2. (a)–(c) Simulated temperature change, (d)–(f) cumulative atmosphere–land CO_2 flux, and (g)–(i) cumulative atmosphere–ocean CO_2 flux from the fully, radiatively, and biogeochemically coupled 1% CO_2 increase simulations for the nine participating models. Note that in (d)–(f) the lines corresponding to the NorESM-ME and CESM1-BGC models essentially overlay each other.

CMIP5: Partition of Carbon

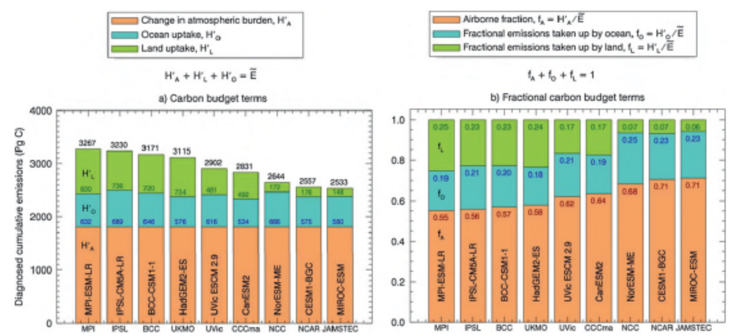
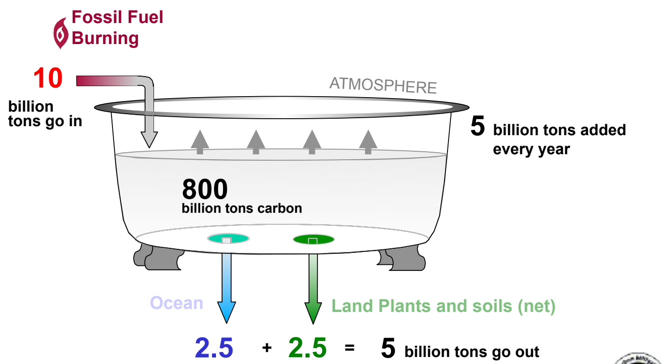


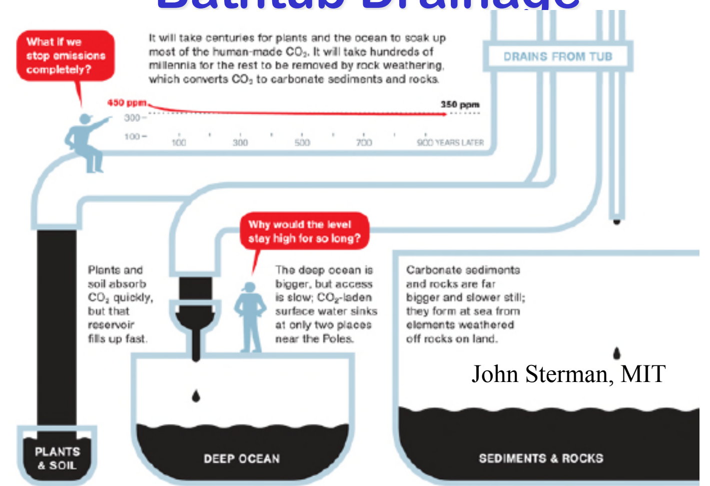
FIG. 3. Components of the atmospheric carbon budget of the participating nine models based on (a) Eq. (7) and (b) Eq. (10) using results from the fully coupled 1% yr^{-1} increasing CO_2 simulation. The terms are based on cumulative fluxes at the time of CO_2 quadrupling 140 yr after the start of the simulation. The models are arranged in a descending order based on their cumulative emissions values. In panel (a) carbon uptake by land and ocean components and diagnosed cumulative emissions and in panel (b) the airborne fraction and fraction of emissions taken up by land and ocean are also noted for individual models.

CO_2 "Budget" of the World



Climate forcing comes from the water, not from the faucet!

Bathtub Drainage



John Sterman, MIT

http://ngm.nationalgeographic.com/big-idea/05/carbon-bath

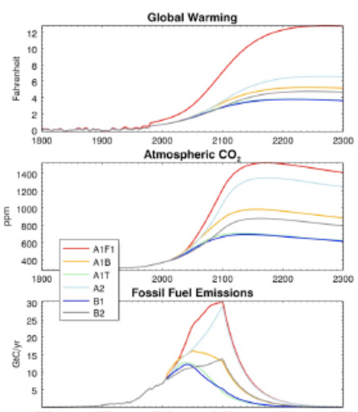
Common Myth #2

"When we reduce or stop the burning of fossil fuel, the CO_2 will go away and things will go back to normal"

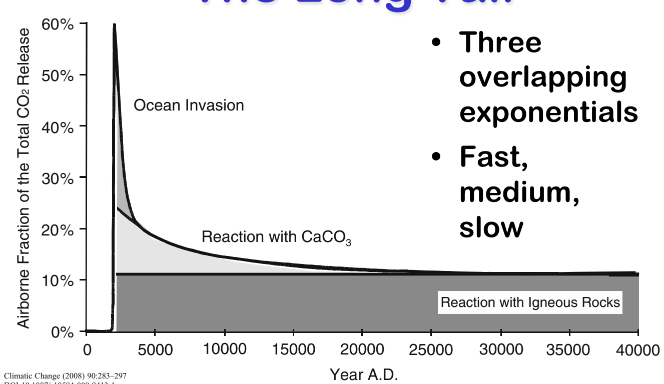
CO_2 from fossil fuel will react with oceans, but only as fast as they "mix"

Eventually, fossil CO_2 will react with rocks

About 1/3 of today's emissions will stay in the air **permanently!**



The Long Tail



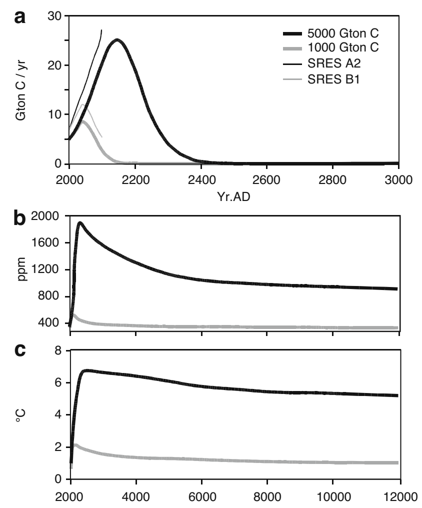
- **Three overlapping exponentials**
- **Fast, medium, slow**

Climatic Change (2008) 90:283–297
DOI 10.1007/s10584-008-9413-1

The millennial atmospheric lifetime of anthropogenic CO_2

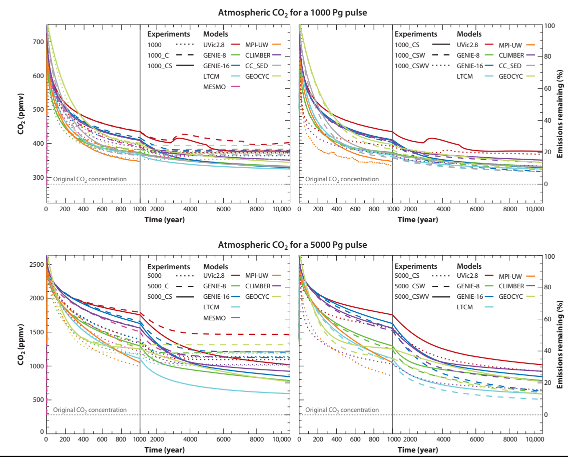
David Archer · Victor Brovkin

Long Tail Depends on Pulse Size



- Larger pulses leave much more work for the slower sinks thousands of years from now
- A2 is on track to exceed 5000 GtC
- B1 is intermediate

Long Tail Intercomparison



Common Myth #2

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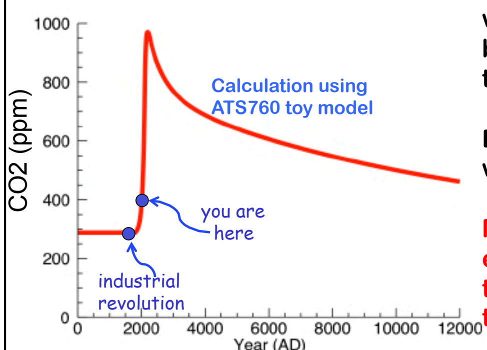
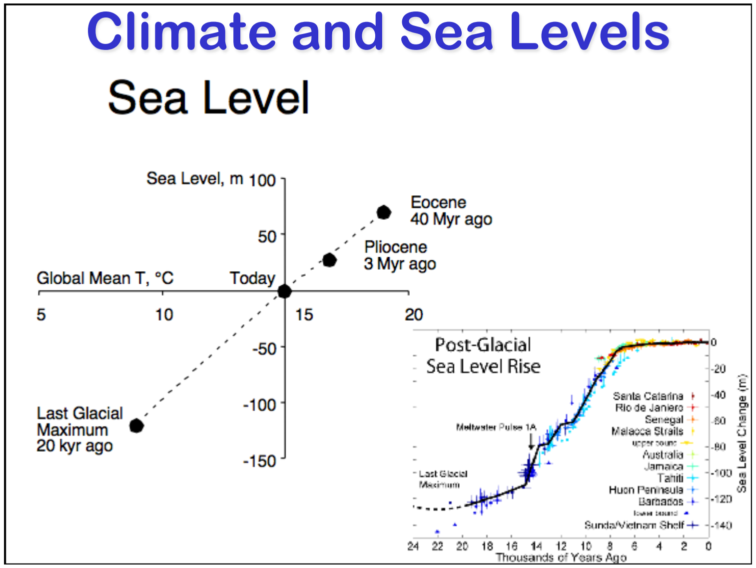


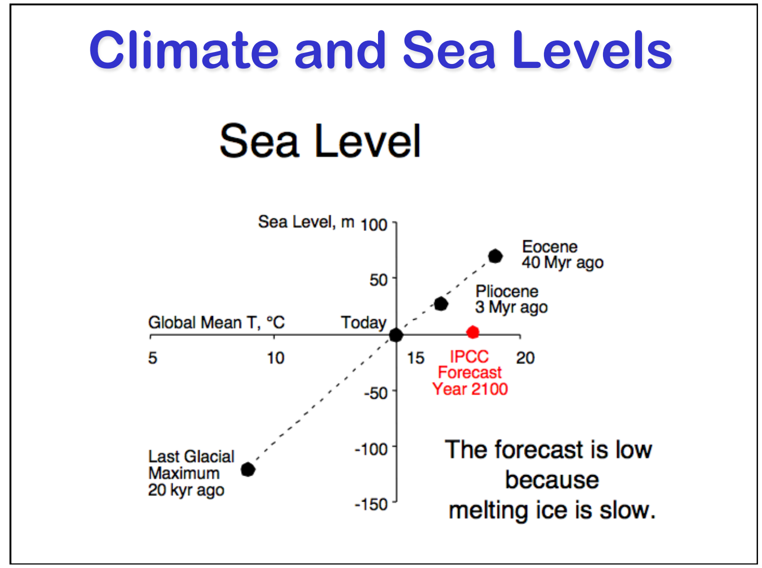
CO_2 from fossil fuel will react with oceans, but only as fast as they "mix"

Eventually, fossil CO_2 will react with rocks

Much of the CO2 we emit now will stay in the air for many thousands of years!

Continental Ice Sheets


Climate and Sea Levels
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
Last Glacial
Maximum
20 kyr ago
Post-Glacial
Sea Level Rise
Meltwater Pulse 1A
Last Glacial
Maximum
Santa Catarina
Rio de Janeiro
Senegal
Malacca Straits
Australia
Jamaica
Tahiti
Huon Peninsula
Barbados
Sunda/Vietnam Shelf
Sea Level Change (m)
Thousands of Years Ago


Climate and Sea Levels
Sea Level
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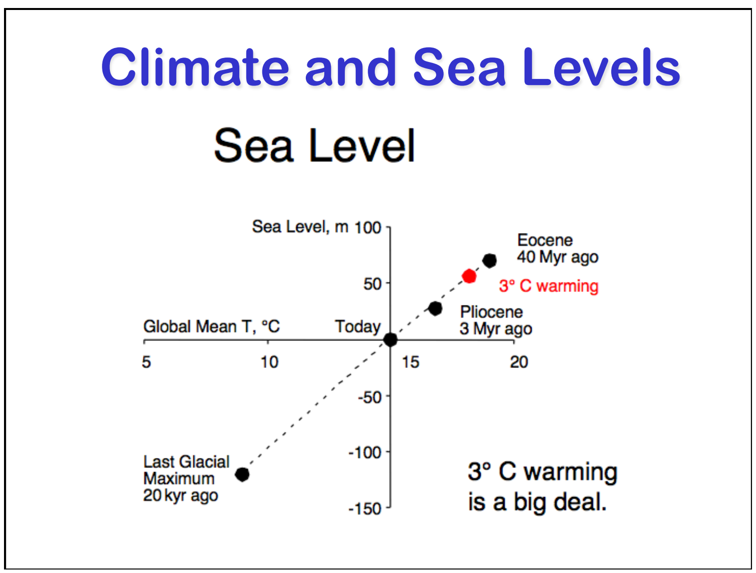
Global Mean T, °C
Today
5
10
15
20
Eocene
40 Myr ago
Pliocene
3 Myr ago
IPCC
Forecast
Year 2100
Last Glacial
Maximum
20 kyr ago
The forecast is low
because
melting ice is slow.


Climate and Sea Levels
Sea Level
Sea Level, m
100
50
-50
-100
-150
Global Mean T, °C
Today
5
10
15
20
Eocene
40 Myr ago
3° C warming
Pliocene
3 Myr ago
Last Glacial
Maximum
20 kyr ago
3° C warming
is a big deal.


Vancouver
Seattle
Portland
San Francisco
Los Angeles
San Diego
Honolulu
Montreal
Halifax
Boston
Philadelphia
New York
Washington, D.C.
Norfolk
Pine Bluff
Charleston
Houston
New Orleans
Tampa
Present-day shoreline
Miami
Havana
Veracruz
Cancún
Port-au-Prince
North America
The entire Atlantic seaboard would vanish, along with Florida and the Gulf Coast. In California, San Francisco's hills would become a cluster of islands and the Central Valley a giant bay. The Gulf of California would stretch north past the latitude of San Diego—not that there'd be a San Diego.
EXIT MAP
North America
South America
Africa
Europe
Asia
Australia
Antarctica
Timeline
http://www.freetech4teachers.com/2013/09/an-interactive-map-of-rising-sea-levels.html