Aspen Global Change Institute

Ocean Carbon Sequestration

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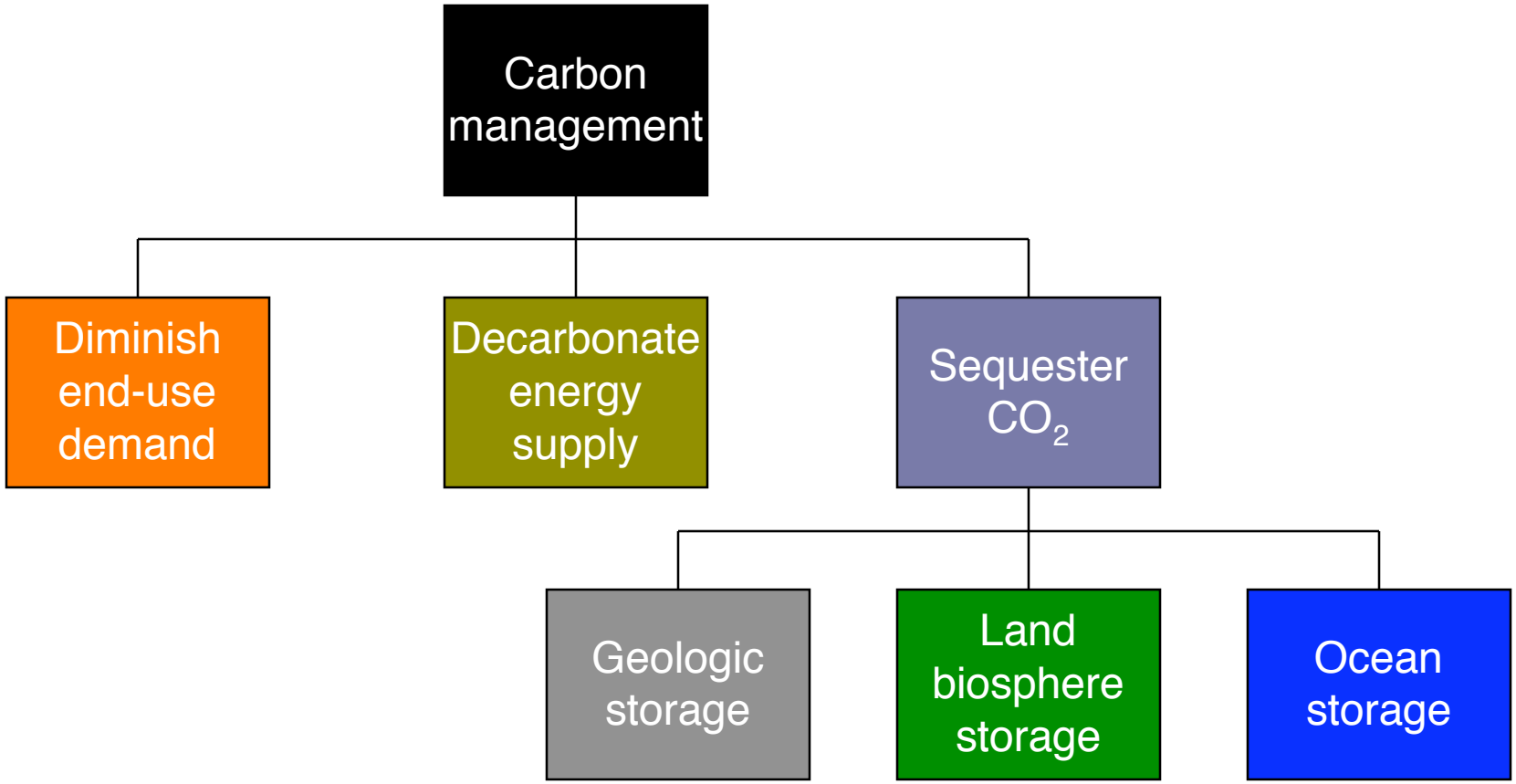
Outline

- Carbon management and ocean sequestration
- Strategies
  - Ocean Fertilization…
  - Direct CO_2 injection
  - Carbonate-dissolution method
- Discussion and conclusions

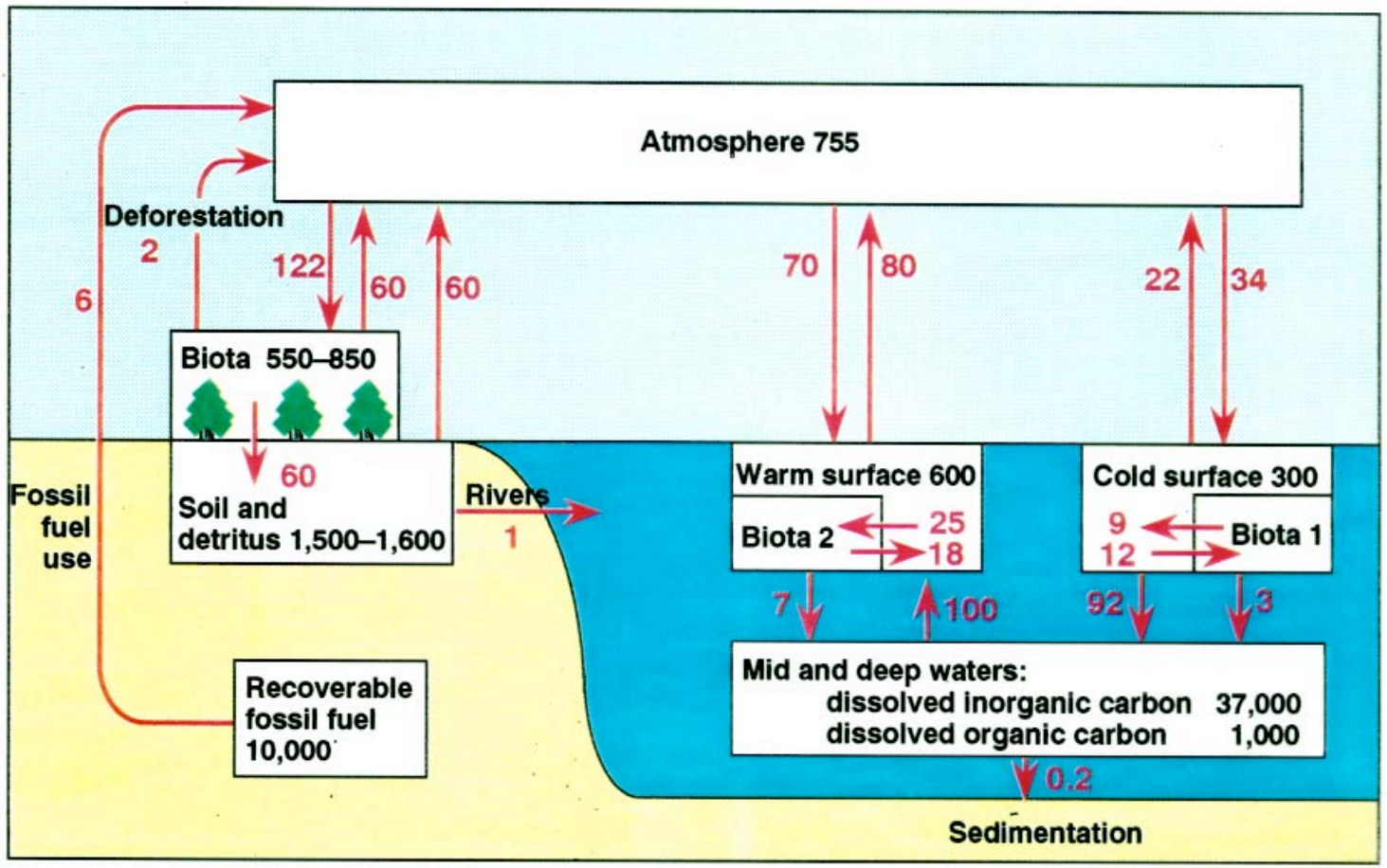
The problem

- We are emitting CO_2 at the rate of ~6 PgC / yr
- This rate will likely increase many-fold over the next century

The DOE carbon management program



Global carbon cycle

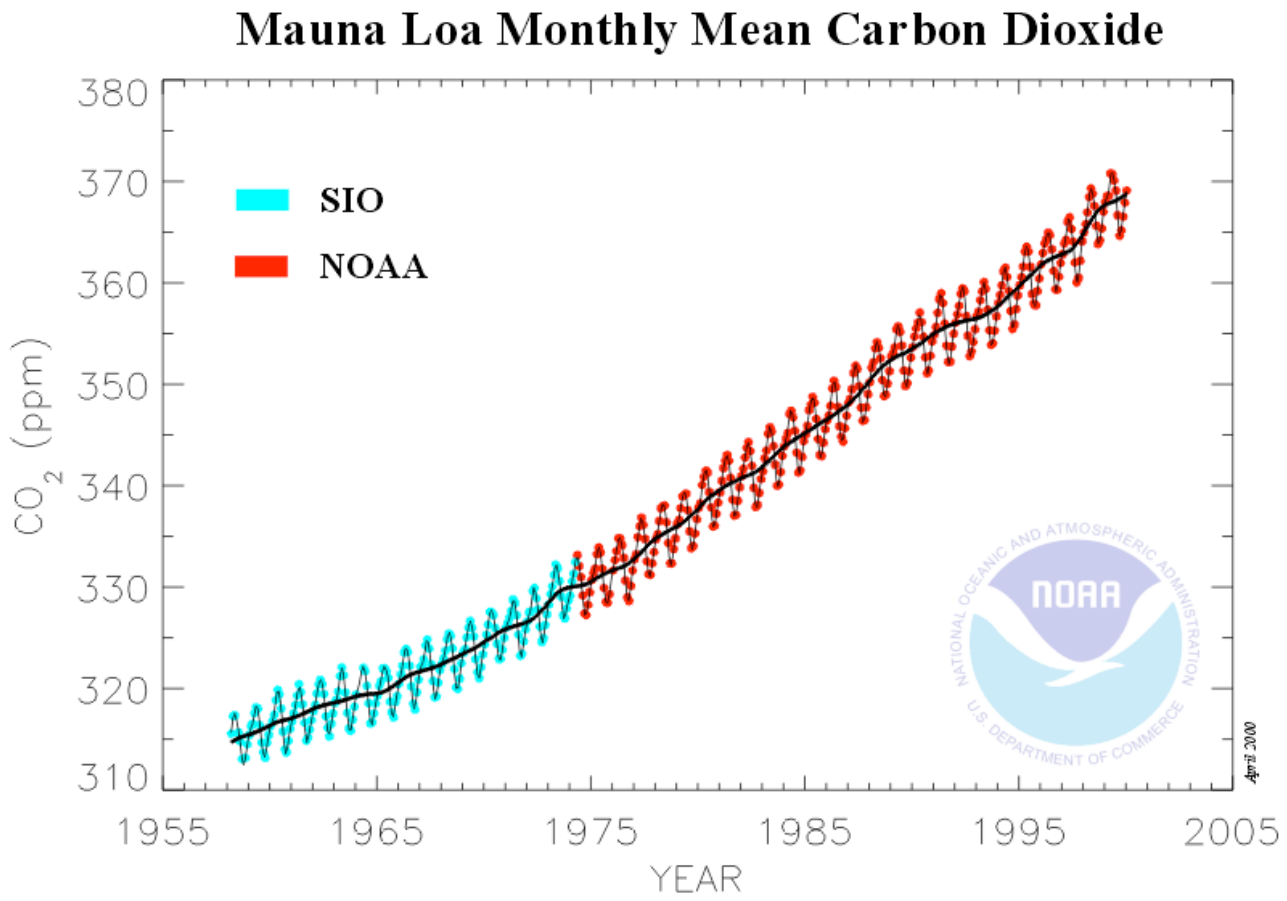


Pools: Gt carbon
Fluxes: Gt carbon per year

yr ~1990

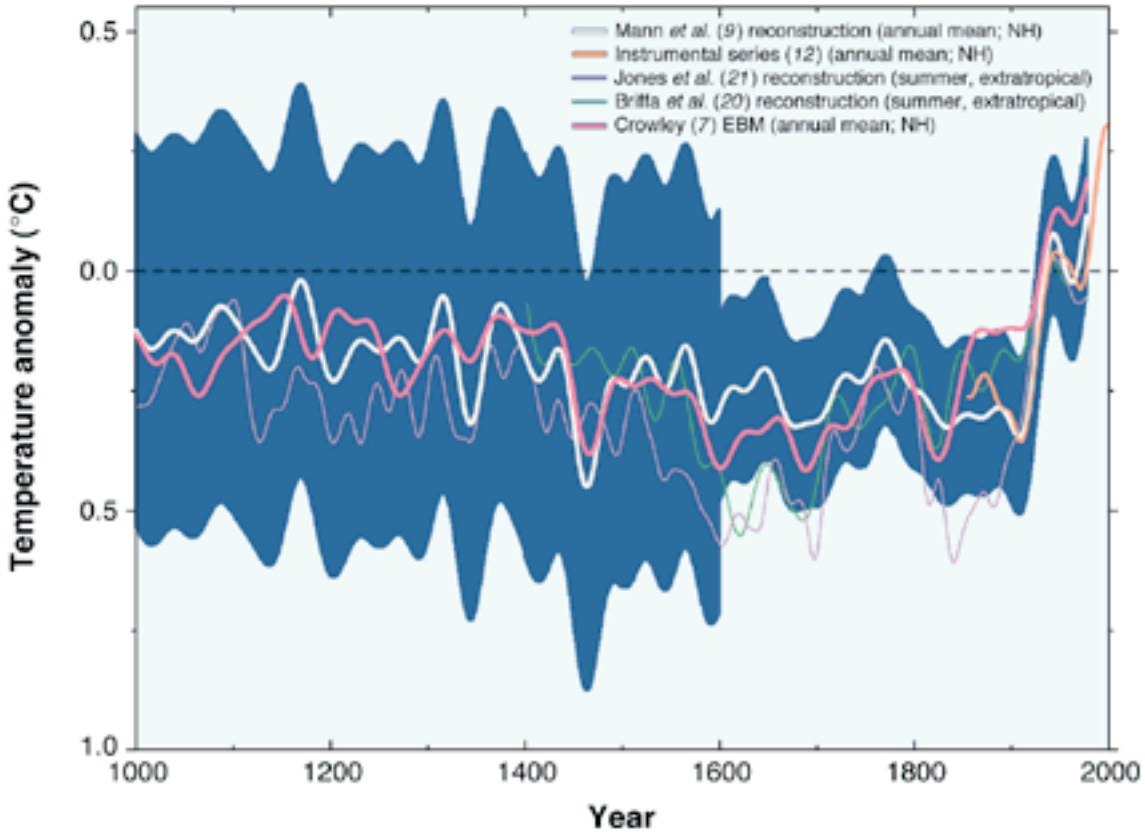
pCO_2 = 354.9 ppm

Atmospheric CO_2 content

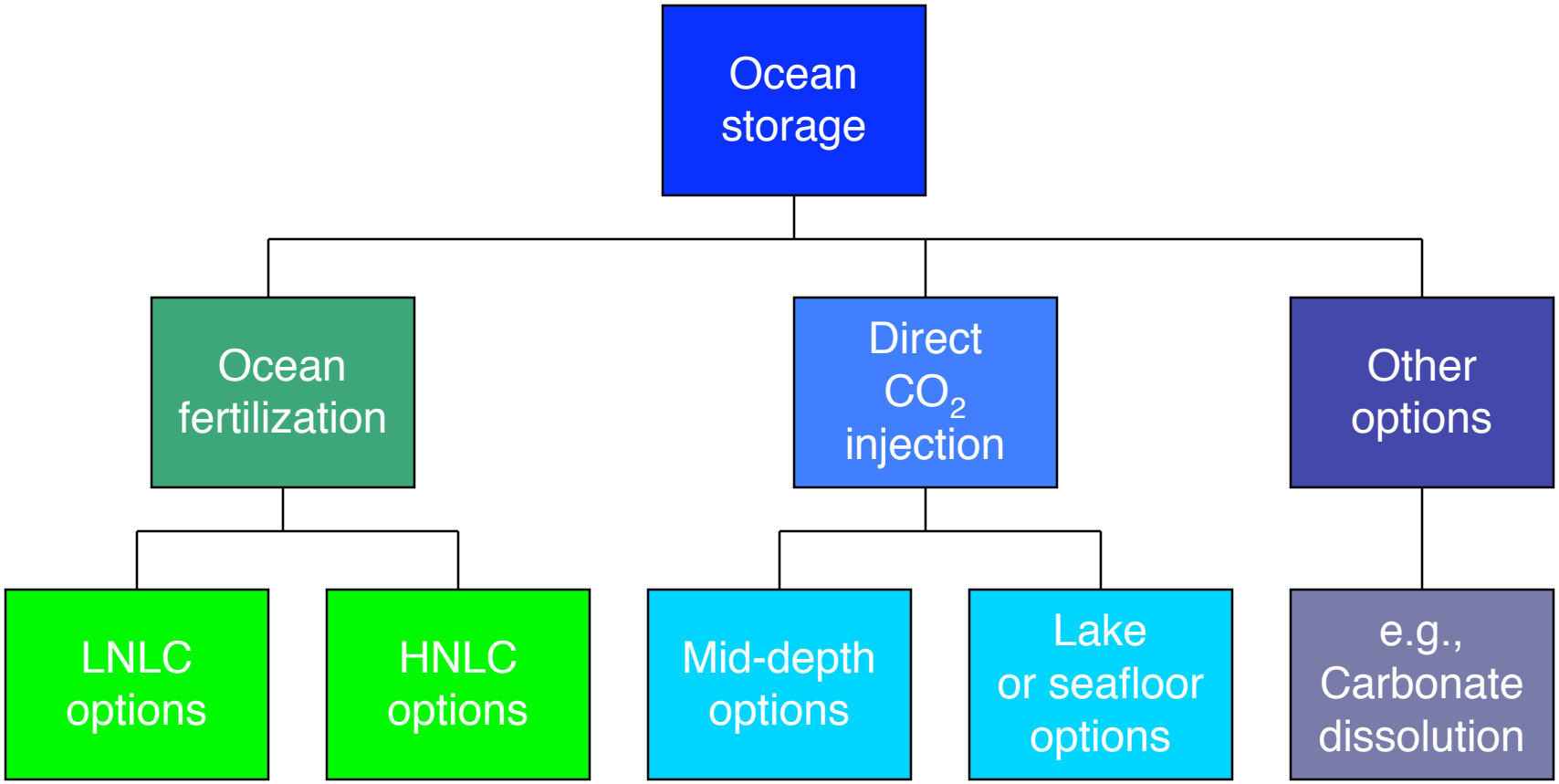


Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Principal investigators: Dr. Pieter Tans, NOAA CMDL Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678, ptans@cmdl.noaa.gov, and Dr. Charles D. Keeling, SIO, La Jolla, California, (616) 534-6001, cdkeeling@ucsd.edu.

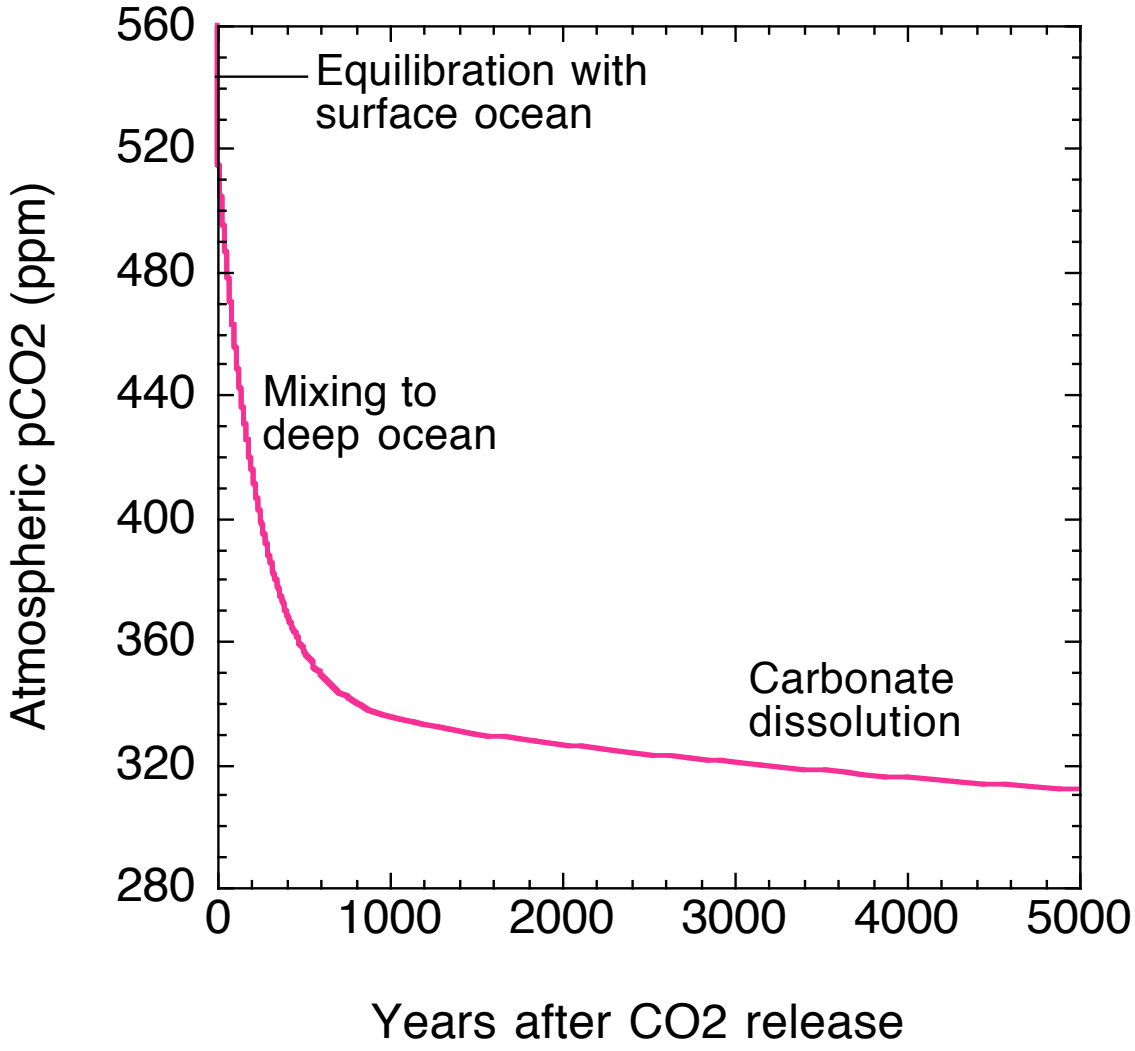
Inferred temperature anomalies



Ocean sequestration options



Release of CO_2 into the atmosphere



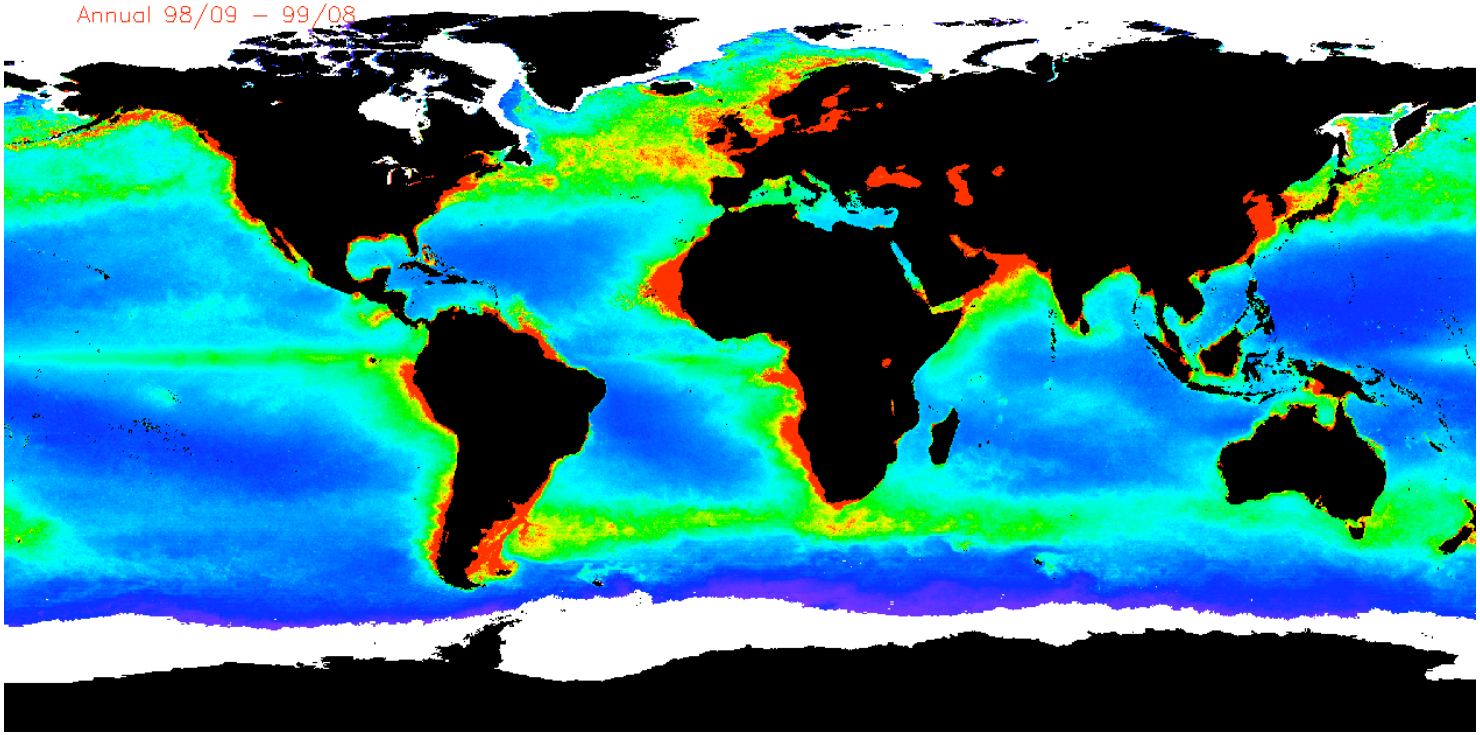
Box-model embedded into a carbonate-silicate-cycle model with carbonate-dissolution and accumulation; described in Caldeira and Rampino (Paleoceanography, 1993)

Carbon removal processes

- CO_2 absorption by surface ocean
  - ~1 yr
    - $CO_2 + H_2O \rightarrow H^+ + HCO_3^-$
- Mixing to deep ocean
  - ~300 yr
- Carbonate dissolution
  - ~6000 yr
    - $CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
- Silicate-rock weathering
  - ~300,000 yr
    - $CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

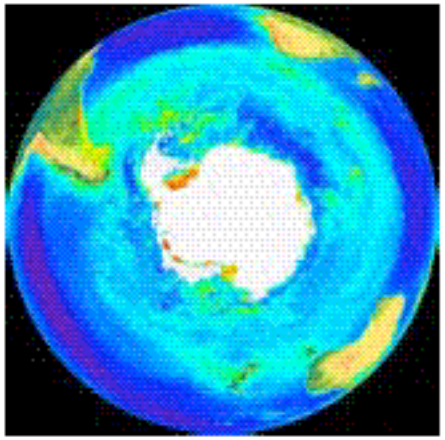
Ocean fertilization

- Idea
  - Increase the net CO_2 flux from the atmosphere to the ocean by increasing the biogenic carbon flux from the near-surface ocean to the ocean interior.



Ocean fertilization

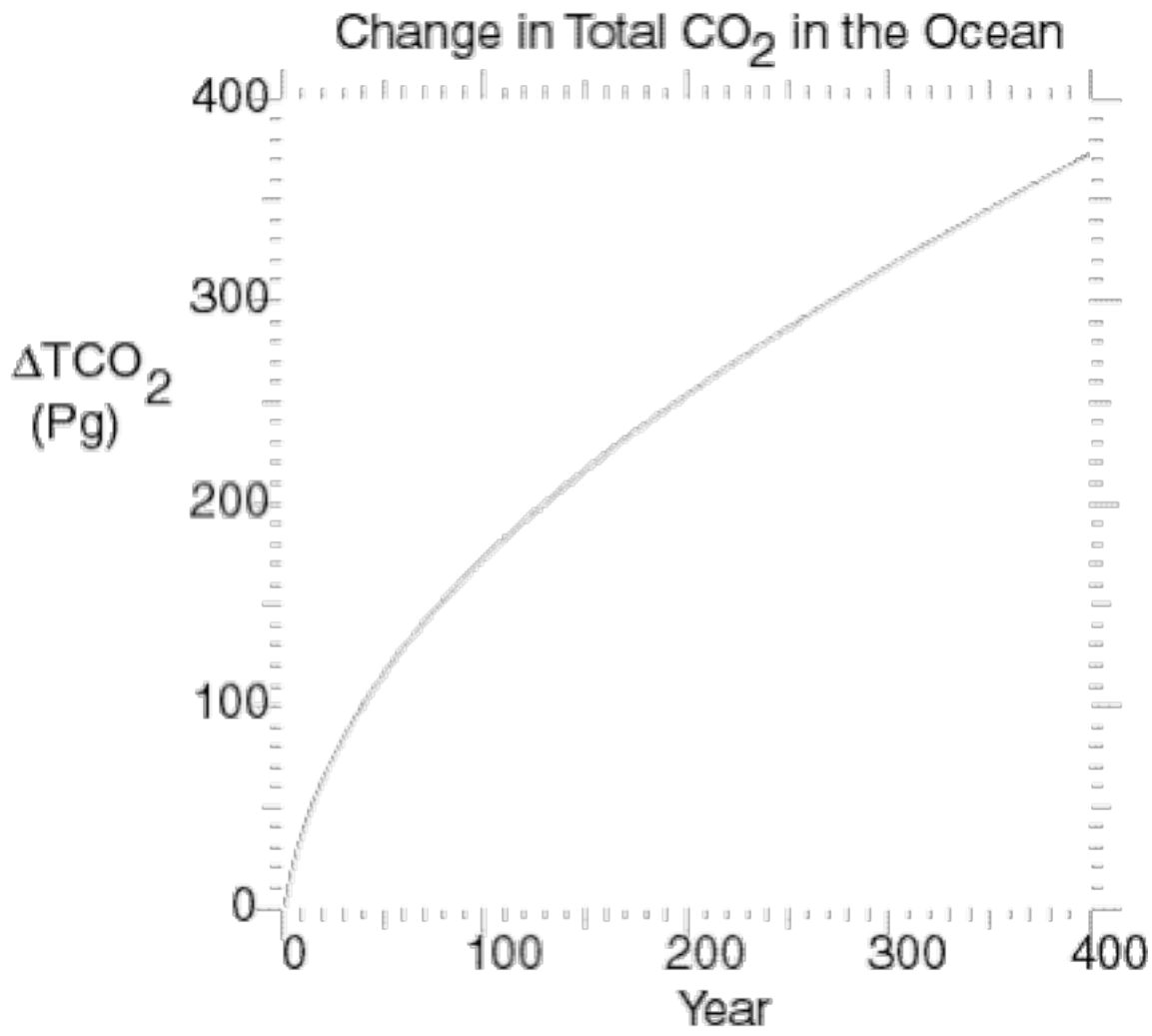
- Research questions
  - What unintended impacts would occur as a result of fertilization?
  - To what extent do various nutrients limit organic carbon transport from the surface ocean to the ocean interior?
  - How long will the exported carbon remain in the ocean interior?



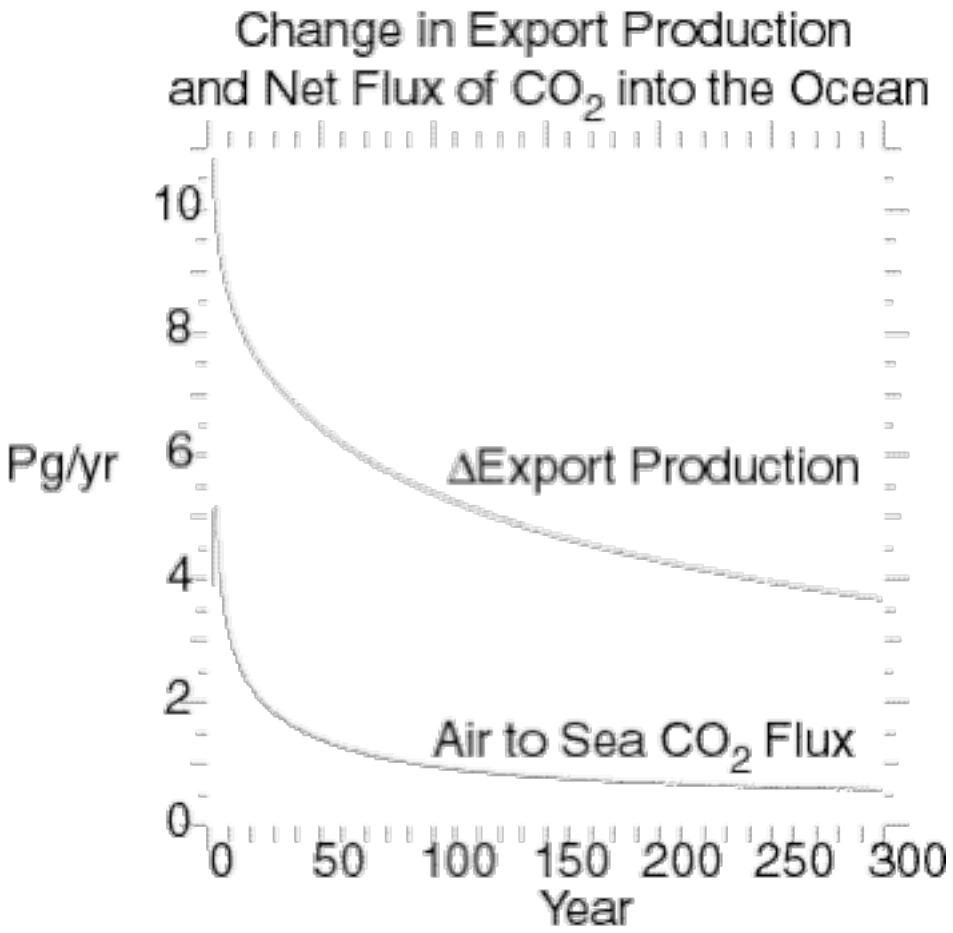
LLNL/DOCS Southern Ocean fertilization simulations

- LANL POP Model
  - NCAR “by-3-prime” configuration
  - Longitudinal resolution ~3.6°
  - Latitudinal resolution ~3°
    - Higher resolution near equator, coarser elsewhere
  - Spin-up
    - Physics and active tracers > 7000 years
    - Biological tracers > 4000 years
      - Most with deep ocean acceleration
- Experiment
  - OCMIP “Biotic” Protocols
  - Continuously utilize all available PO_4 south of 31°S

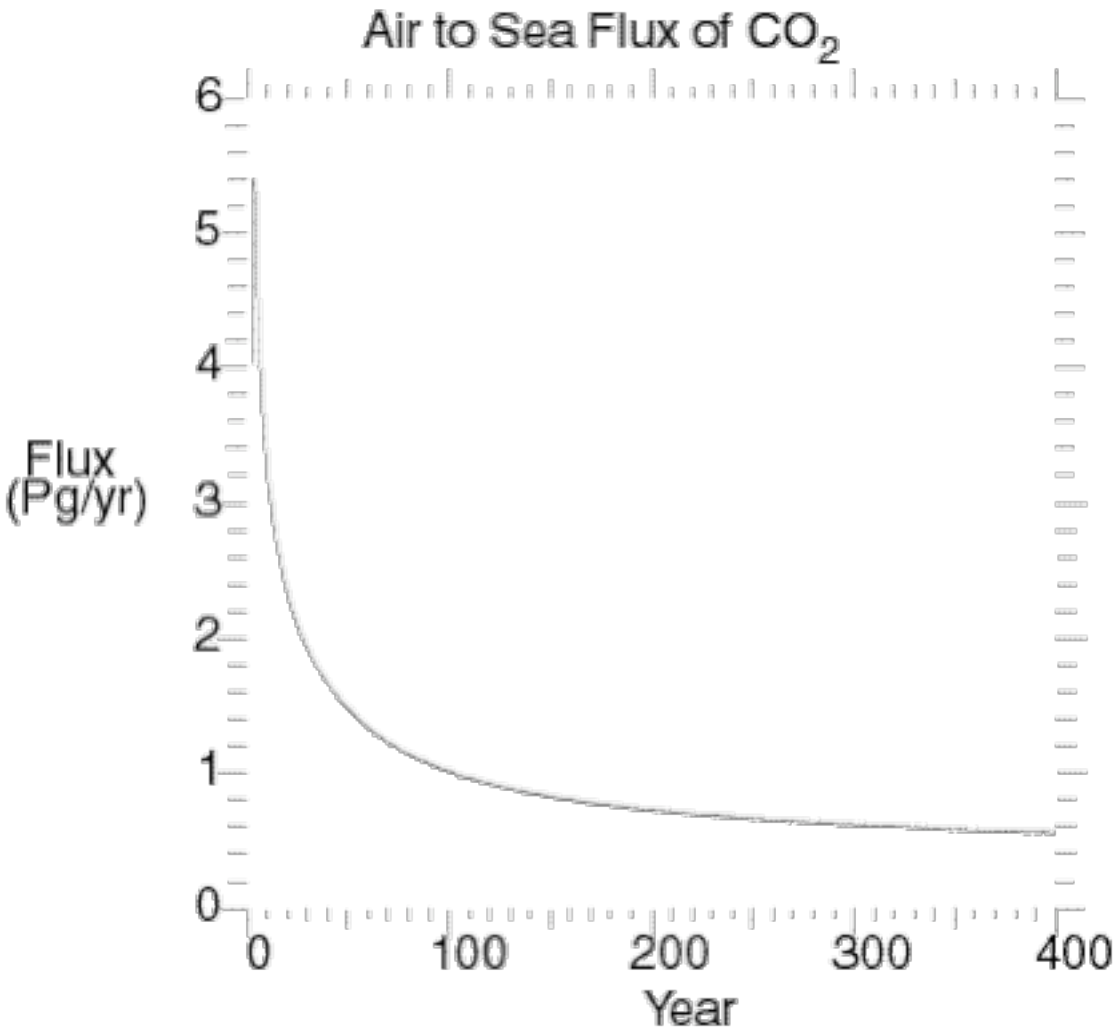
Southern Ocean fertilization simulations



Southern Ocean fertilization simulations



Southern Ocean fertilization simulations



Southern Ocean fertilization simulations

Effect of fertilizing entire ocean south of 30°S for one year

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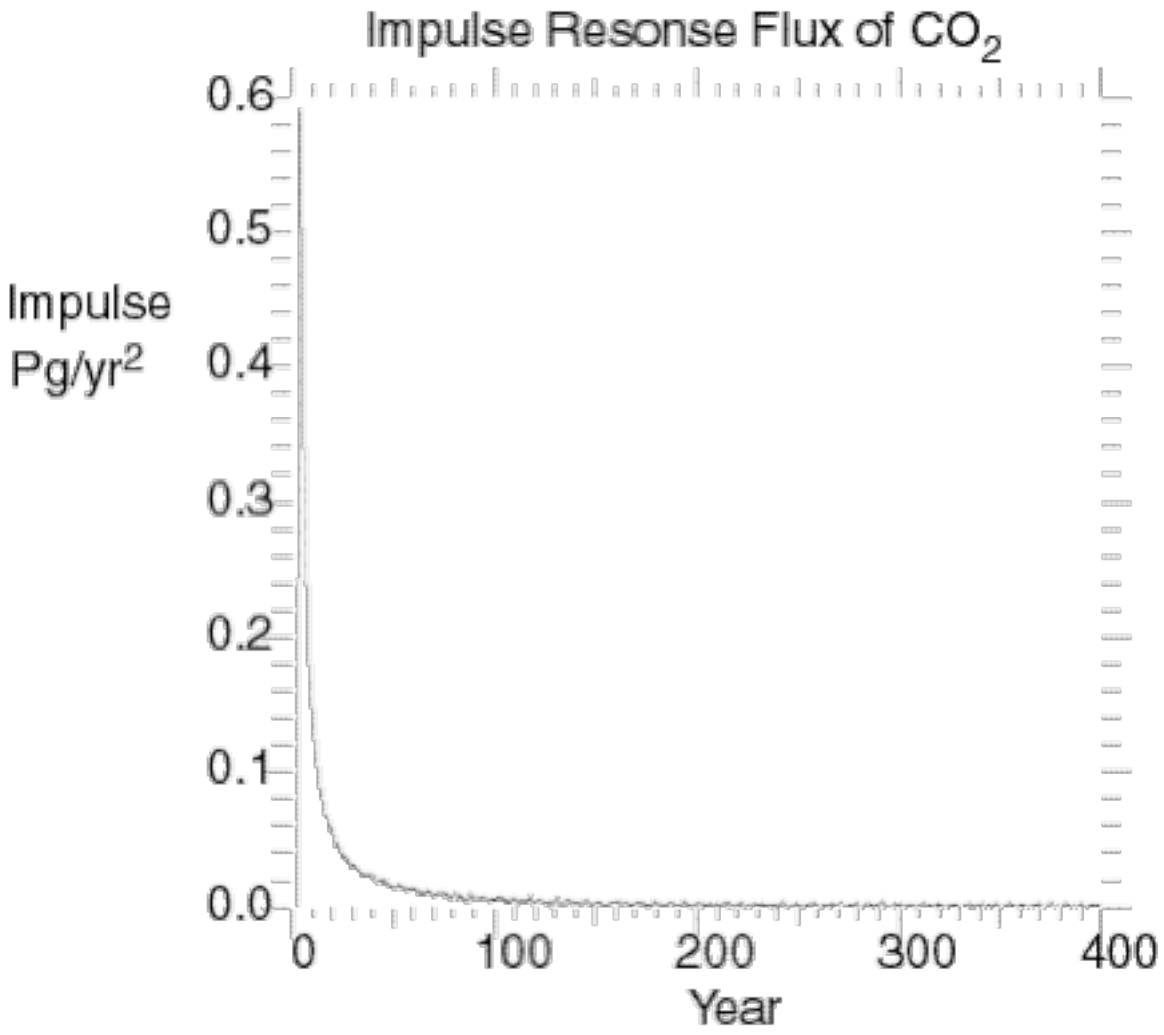
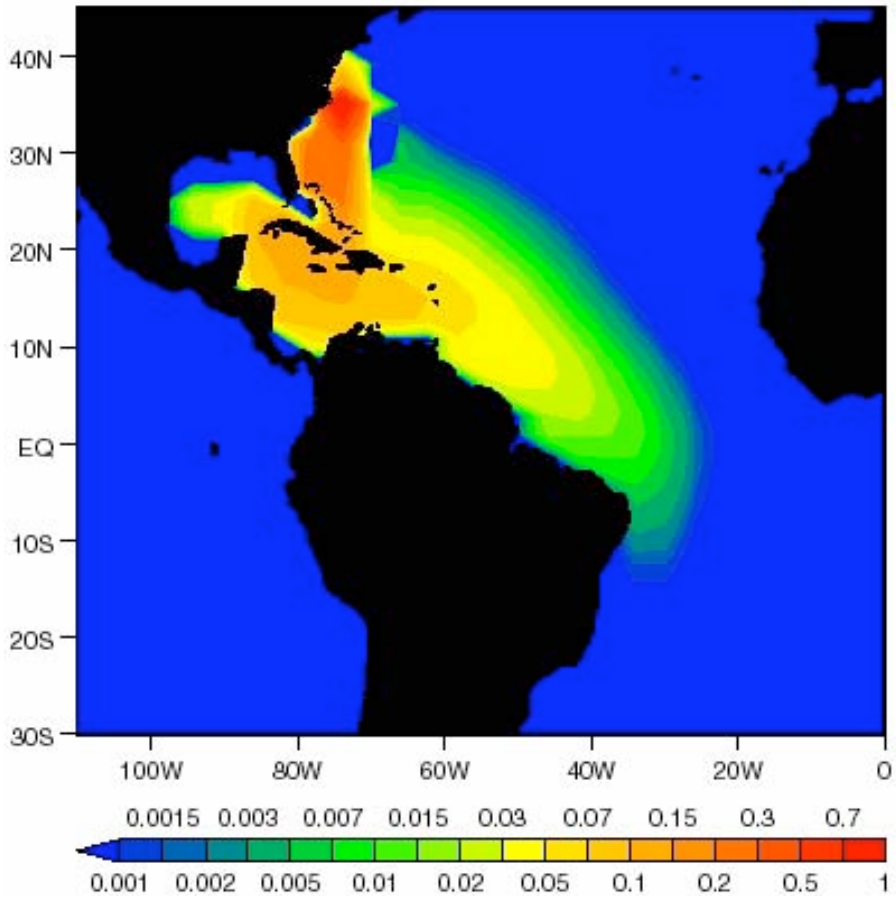
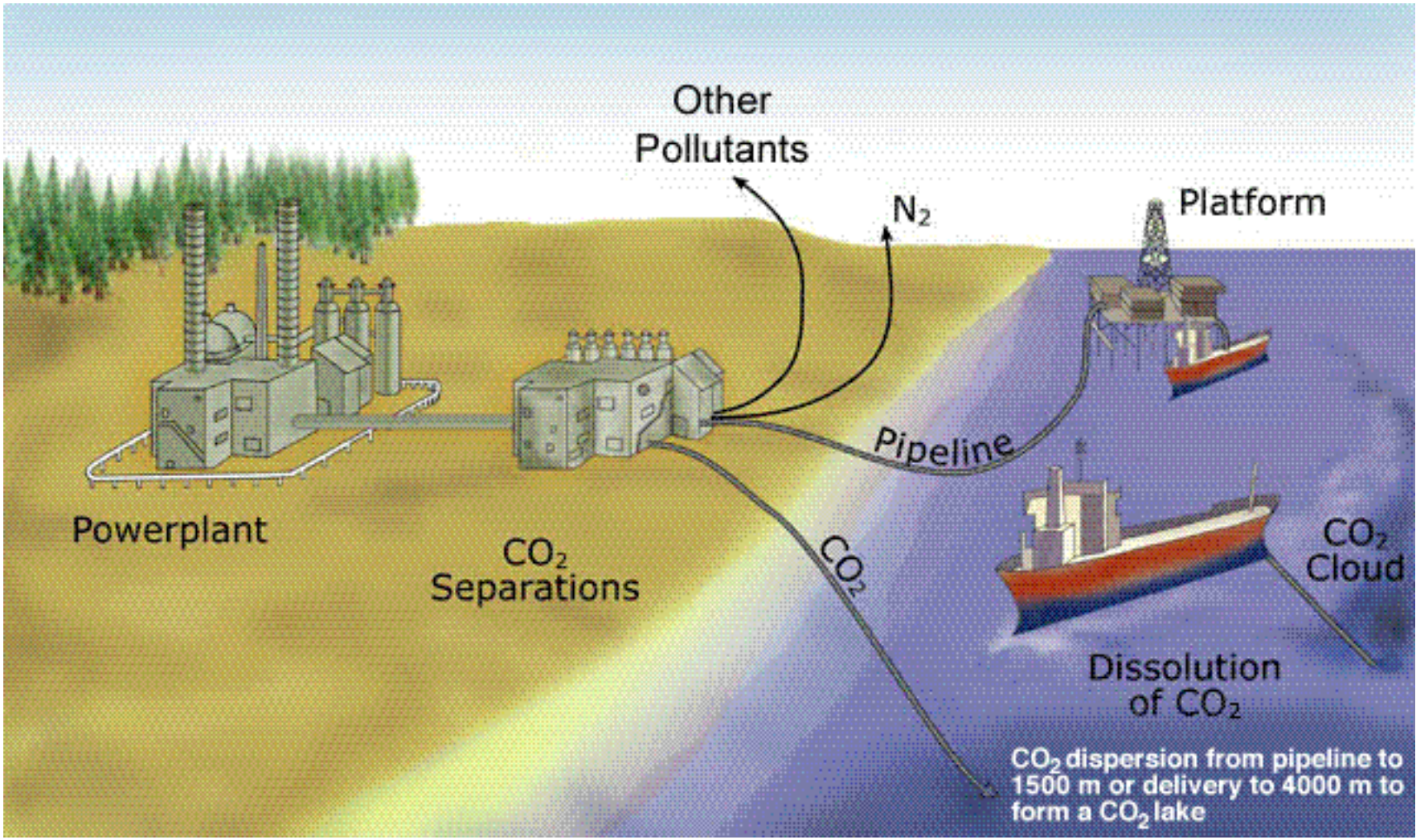


Direct CO_2 injection

- Idea
  - Bypass typical ocean-atmosphere mixing time-scale (~300 yr?) by directly injecting CO_2 into the ocean interior.

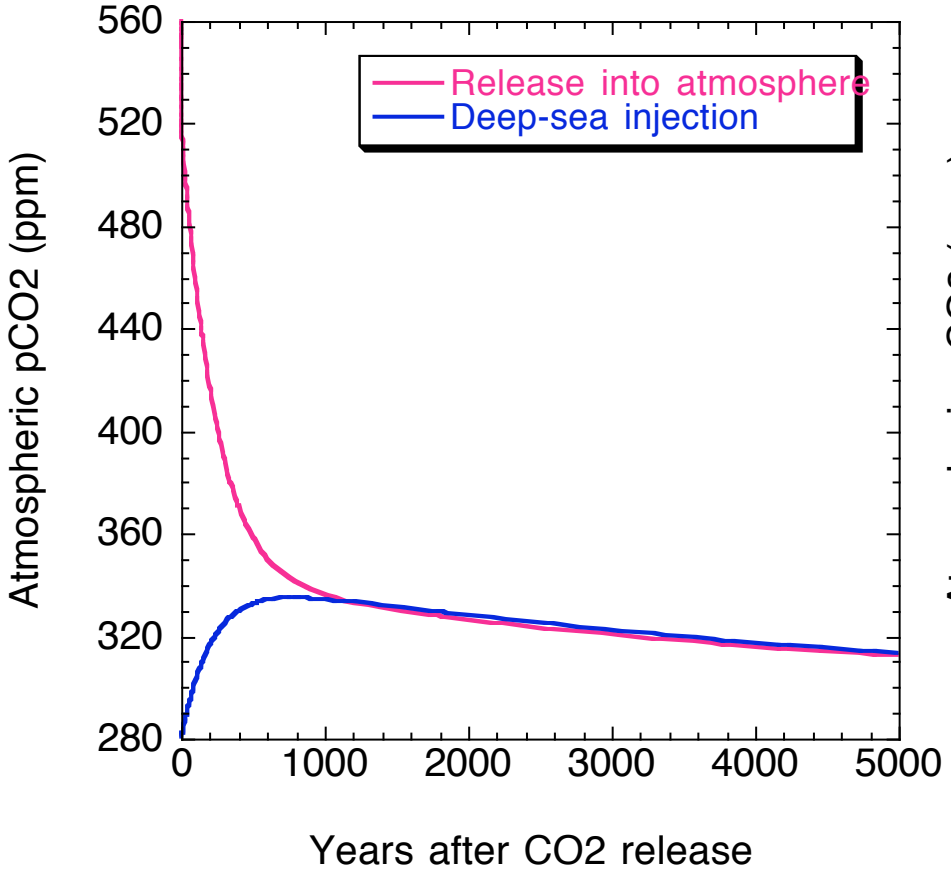


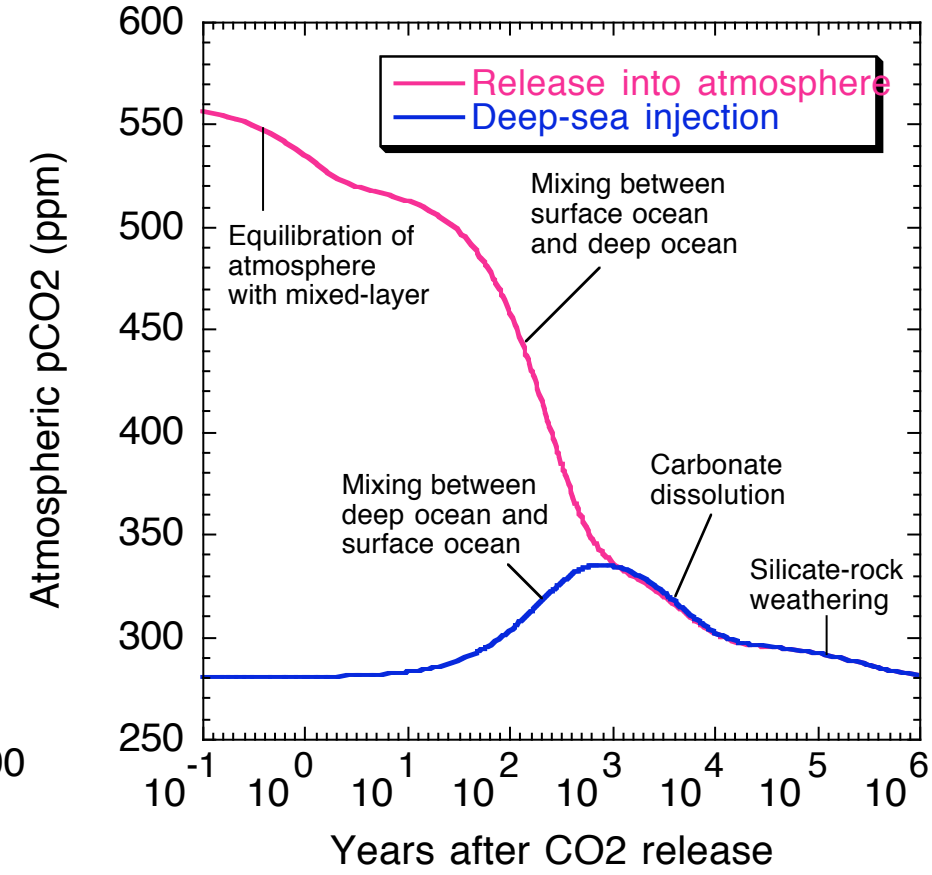
Direct CO_2 injection



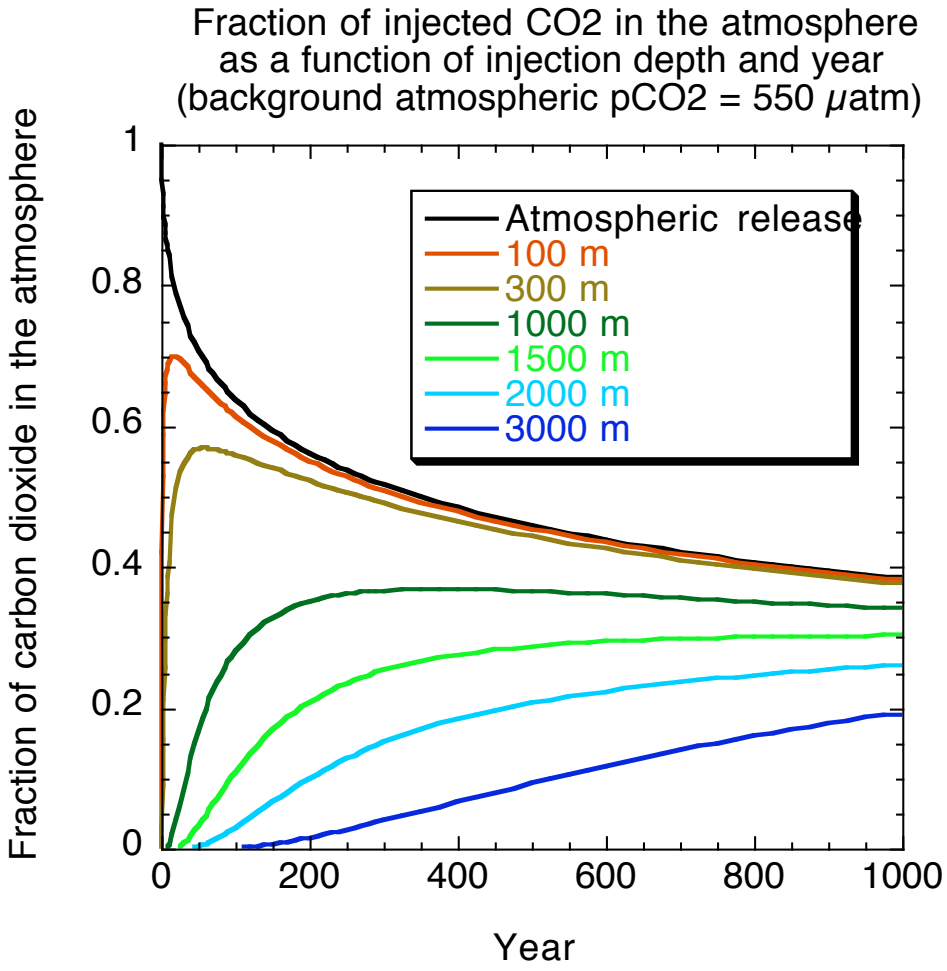
Deep-sea CO_2 injection

- Direct CO_2 injection has been proposed as an effective means of
  - diminishing future climate change
  - with minimal economic and environmental damage

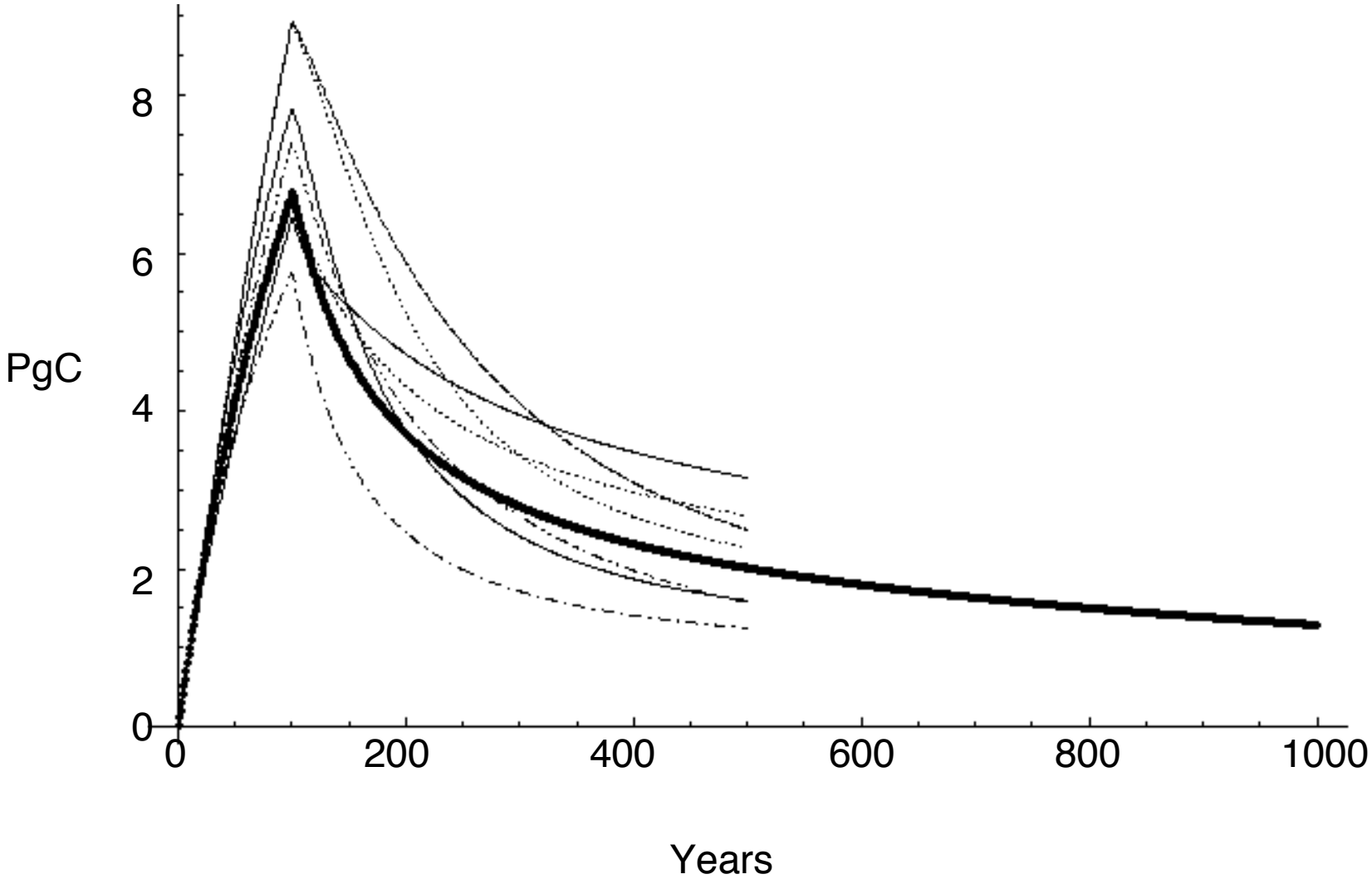




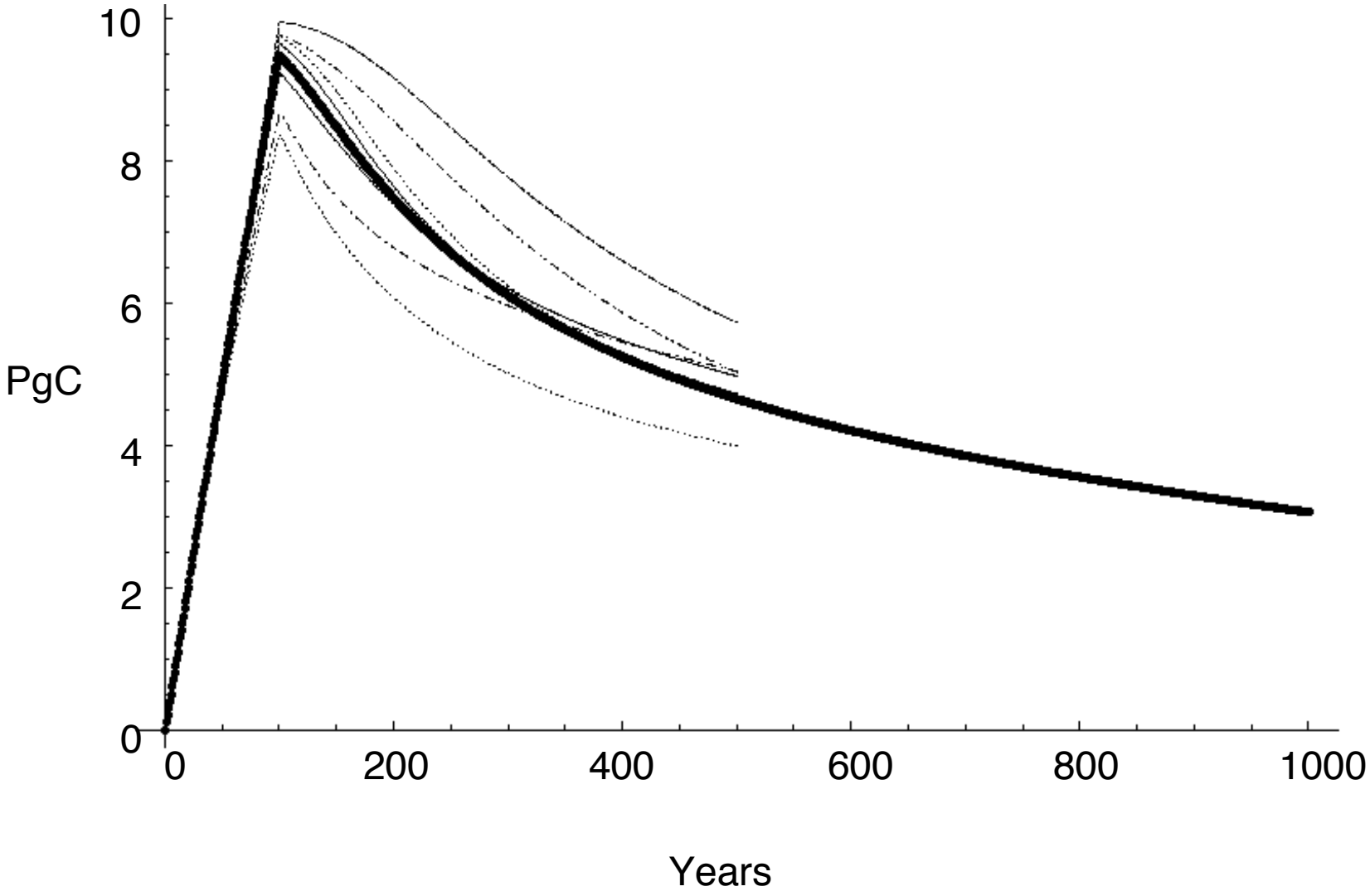
Direct CO_2 injection into the ocean interior can slow the accumulation of CO_2 in the atmosphere



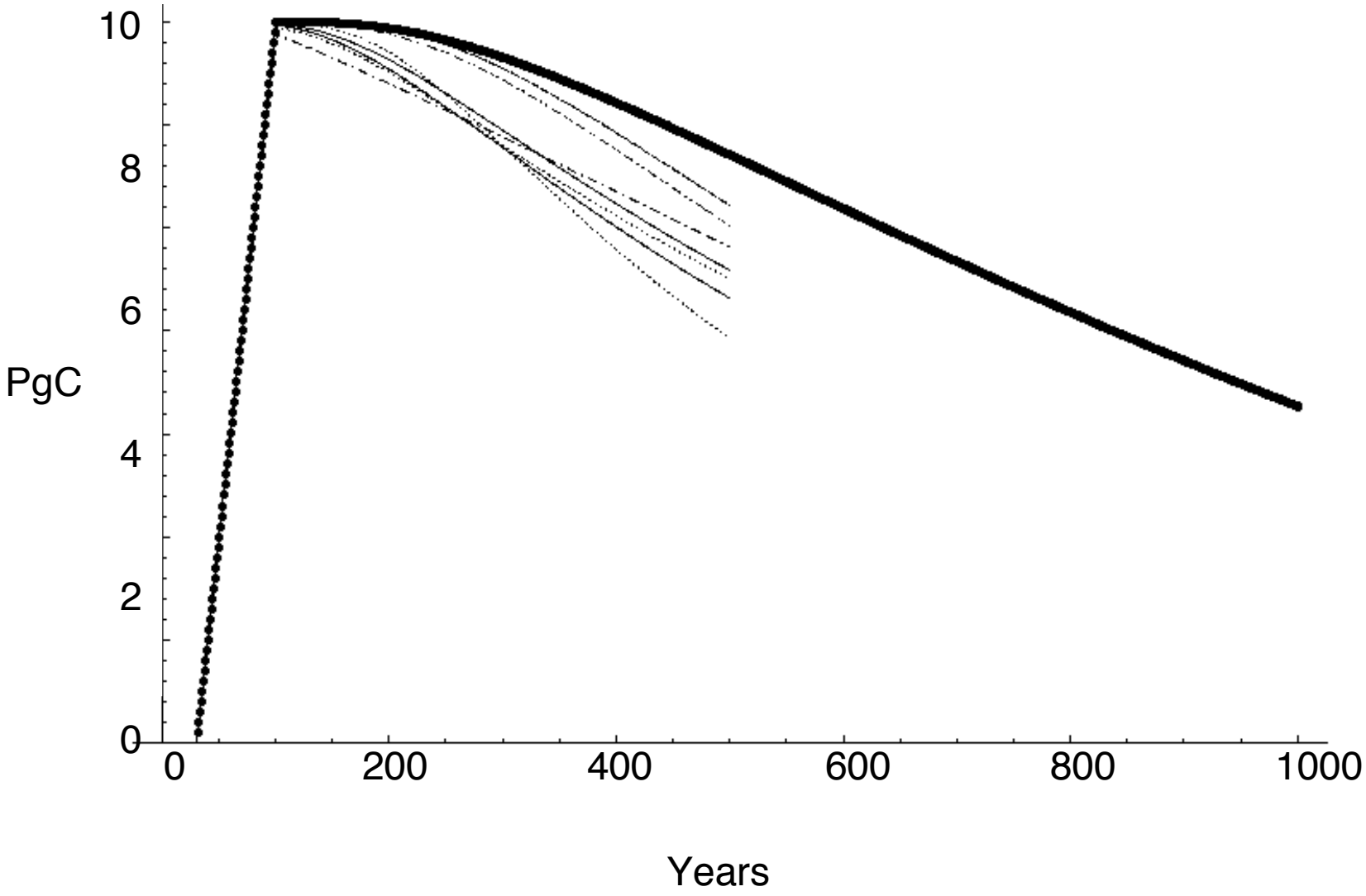
Direct CO_2 injection
Comparison of 3D and 1D models at 800 m depth



Direct CO_2 injection
Comparison of 3D and 1D models at 1500 m depth



Direct CO_2 injection
Comparison of 3D and 1D models at 3000 m depth



Direct CO_2 injection simulations

- Simulations performed at 1° by 1° using the DOCS/LLNL model
- 0.1 PgC / yr continuous injection
- 2 injection locations
  - New York
  - San Francisco
- 2 injection depths
  - 710 m
  - 3025 m

Column inventory

Surface Fluxes

Carbon removal processes

- CO_2 absorption by surface ocean
  - ~1 yr
    - $CO_2 + H_2O \rightarrow H^+ + HCO_3^-$
- Mixing to deep ocean
  - ~300 yr
- Carbonate dissolution
  - ~6000 yr
    - $CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
- Silicate-rock weathering
  - ~300,000 yr
    - $CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

Carbonate-dissolution method: Basic idea

- Instead of waiting for nature to dissolve the carbonate,
  - bring CO_2-rich waste gas in contact with seawater in a reactor vessel at the power plant to produce carbonic acid
    - $CO_2 + H_2O \longrightarrow H^+ + HCO_3^-$
  - use this carbonic acid to dissolve crushed limestone
    - $H^+ + HCO_3^- + CaCO_3 \longrightarrow Ca^{2+} + 2\ HCO_3^-$
  - dilute the resulting solution in the near-surface ocean

Carbonate-dissolution method: Steps

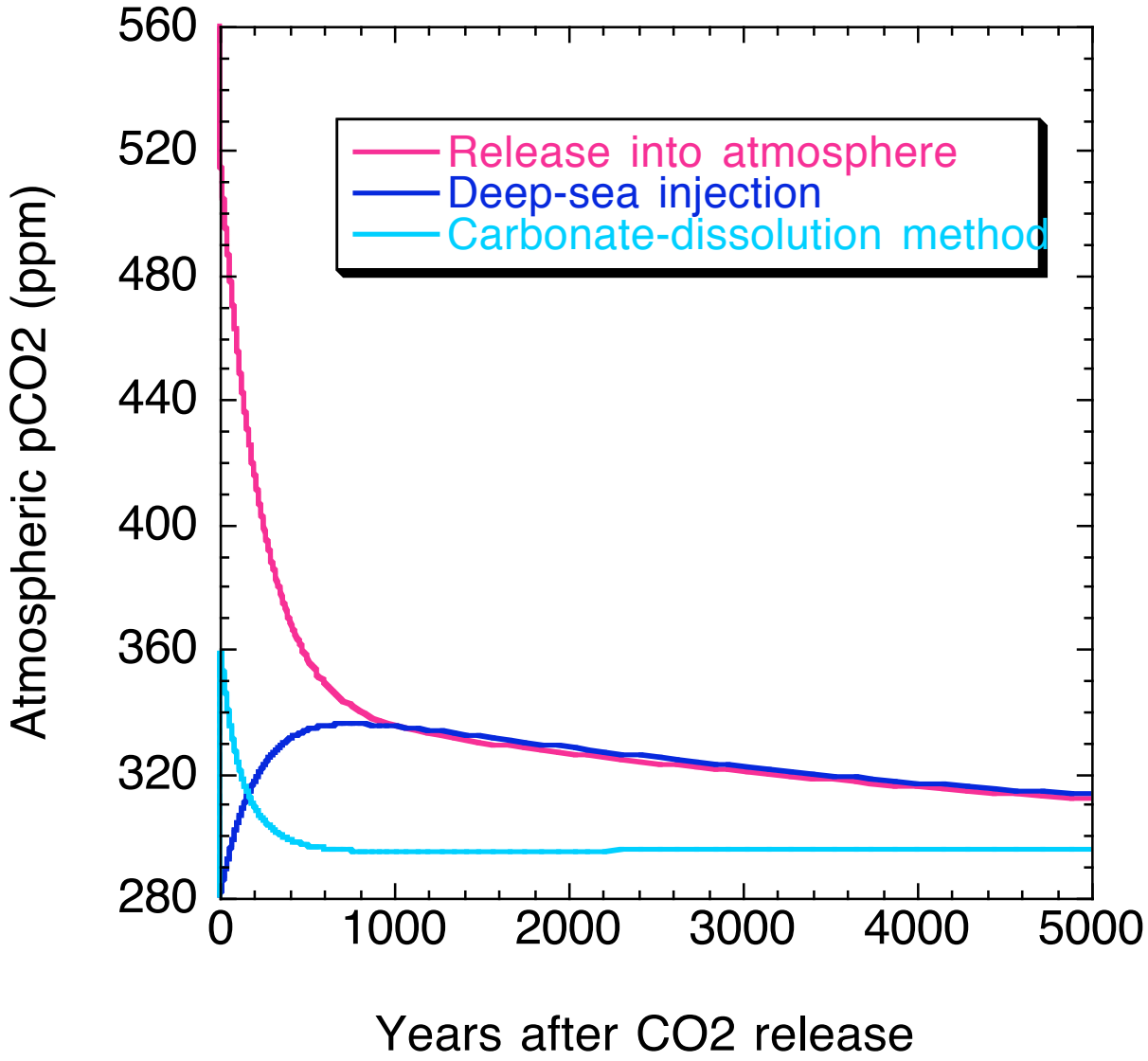
- Bring seawater into contact with CO_2-rich power-plant flue gases (possibly cleaned and/or pressurized)
- Bring CO_2-enriched seawater into contact with crushed carbonate (e.g., $CaCO_3$)
- Dissolve carbonate
- Degas some CO_2 from effluent and recycle into reactor
- Release effluent for dilution in ocean

Carbonate-dissolution method: chemistry

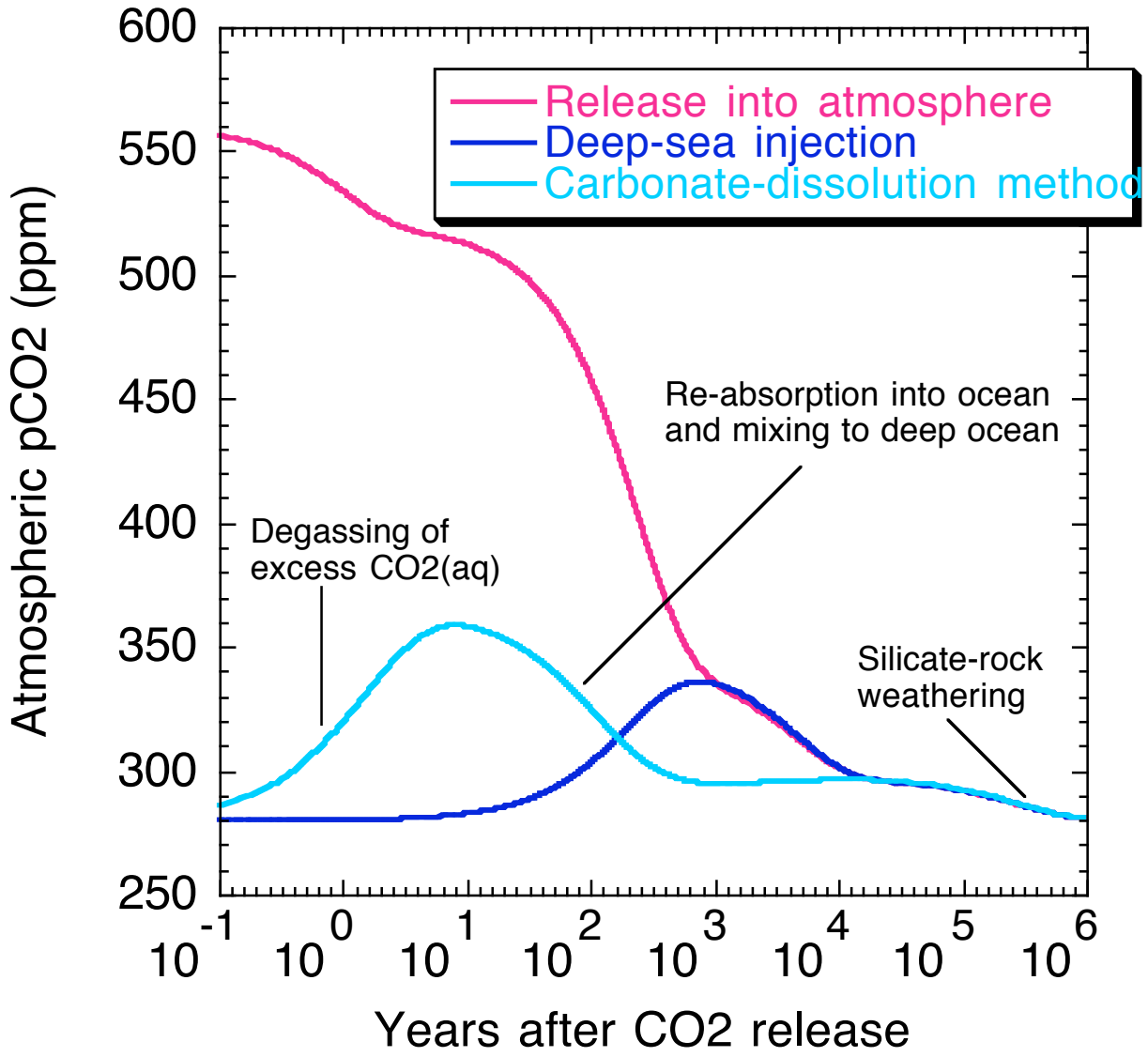
	(A) seawater in equil. with atm CO_2	(B) seawater in equil. with 0.15 atm CO_2	(C) in equil. with 0.15 atm CO_2 and calcite	(D) degassed to seawater $\Omega_{Calcite}$	(E) diluted with 100 parts seawater	(F) degassed to equil. with atm.
pCO_2 (µatm)	350	150000	150000	35339	415	350
∑Alk (µeq/kg)	2314	2314	14808	14808	2438	2438
$\sum CO_2$ (µmol/kg)	2047	7459	19921	15893	2184	2149
CO_2 (aq) (µmol/kg)	12	5143	5143	1212	14	12
HCO_3^- (µmol/kg)	1844	2315	14749	14563	1983	1928
$CO3_2^-$ (µmol/kg)	191	1	29	118	187	209
Ca^{2+} (mmol/kg)	10.12	10.12	16.37	16.37	10.18	10.18
$\Omega_{Calcite}$	4.14	0.02	1.00	4.14	4.14	4.56
pH	8.22	5.69	6.50	7.12	8.18	8.24
$ffCO_2$ /$CaCO_3$ dissolved			1.86	1.22	1.22	0.66

Carbonate chemistry calculated as described by Takahashi et al. (1982) and Peng et al. (1987). Calculations reported in Caldeira and Rau (in press).

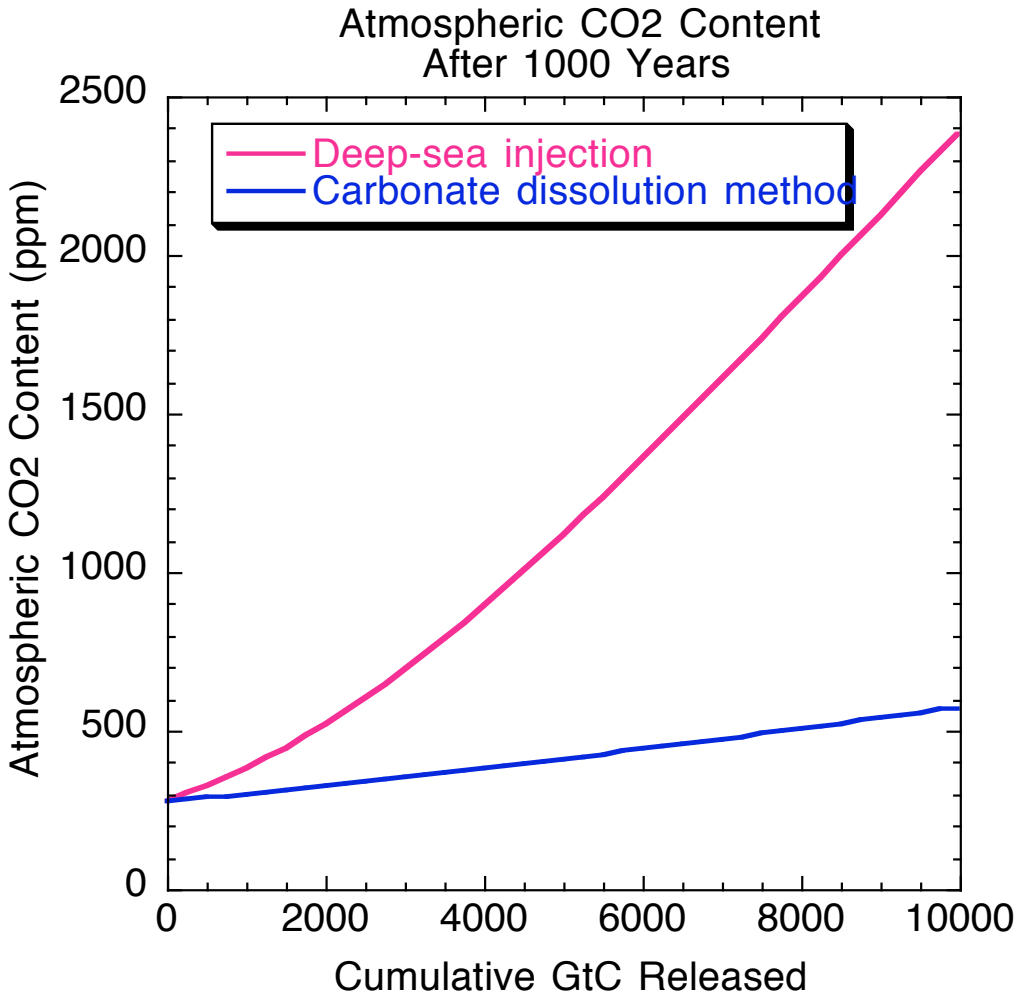
Carbonate-dissolution method



Carbonate-dissolution method



Carbonate-dissolution increases long-term effectiveness of carbon sequestration



Carbonate-dissolution method: Costs

- Estimated cost per tonne CO_2 sequestered, assuming coastal location
  - 2.3 tonnes limestone @ $4/tonne = $ 9.20
  - limestone crushing from 10 cm to 1cm = $ 1.45
  - limestone transport 150 km by rail = $12.08
  - water pumping cost, 10^4 m^3, 3 vertical m = $ 2.85
  - capital cost = $ 2.00
  - operations and maintenance = $ 0.50

- TOTAL: using rail = $ 33
  using barge = $ 23

- Estimated cost of CO_2 separation using available technologies $ 40

Summary of carbon-dissolution method

- The carbonate-dissolution method for ocean sequestration of CO_2
  - no exotic reactants
  - waste products occur naturally in ocean
  - uses existing simple technologies
  - long-term geochemical advantages
  - could be cost-effective (or could be prohibitively expensive)
- Favored application: coastal CO_2 point sources
- This method can be used in tandem with other sequestration methods

Overview

- Fertilization
  - Relatively inexpensive
  - Strategy seeks to maximize biological impact
  - Maximum long-term flux may be < 1 PgC / yr
- Direct injection
  - Separation is cost driver
  - Probably more benign than CO_2 injection into the atmosphere
  - Effective in reducing atmospheric CO_2 for hundreds of years
- Carbonate-dissolution
  - Cost is highly uncertain
  - Minimum ocean biological impact (limestone mining impact ?)
  - Highly effective, if feasible