Workshop on Carbon Sequestration Science

Ocean Carbon Sequestration

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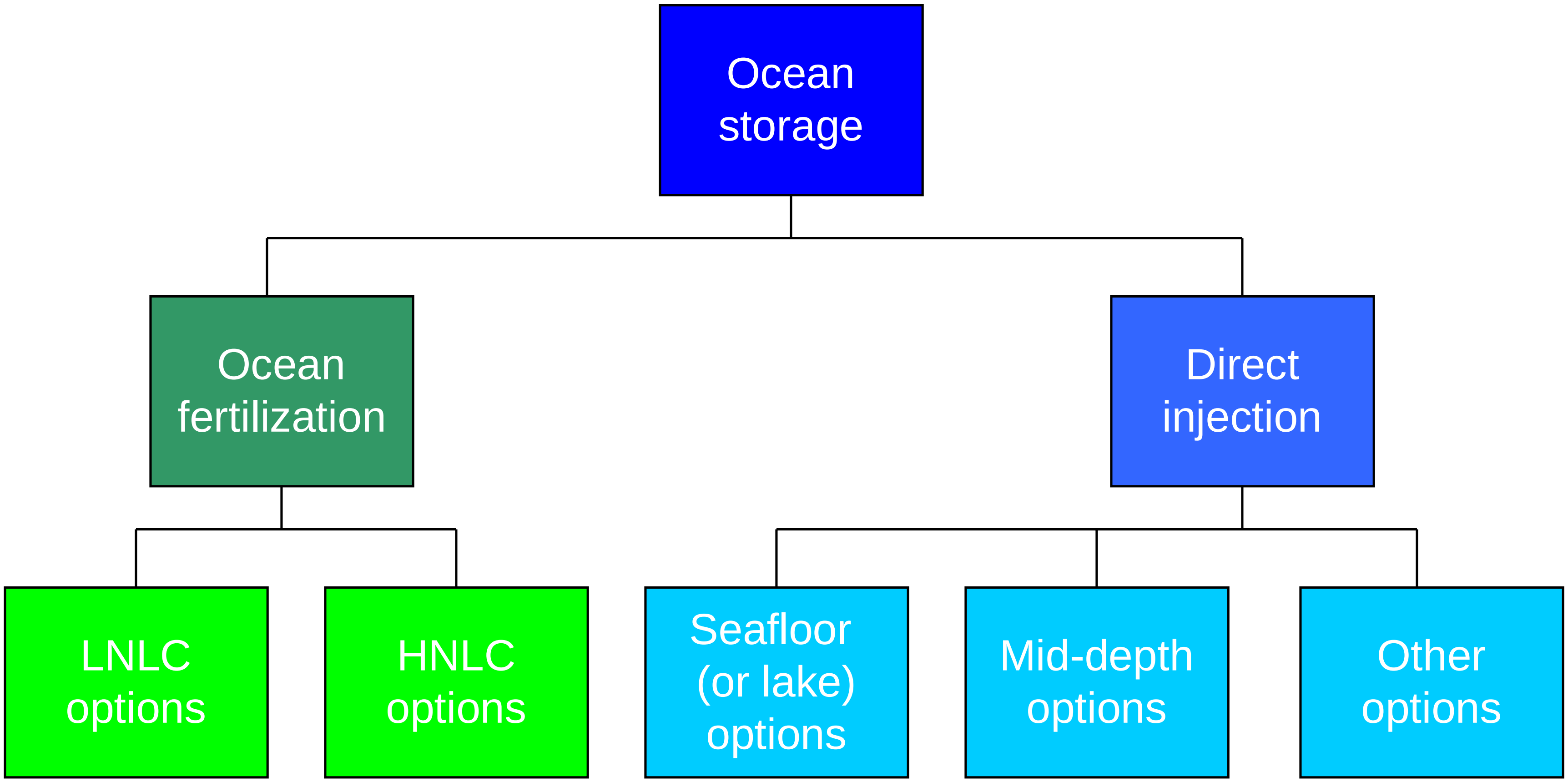
Ocean Carbon Sequestration Options

- The direct injection of a relatively pure CO_2 stream that has been generated, for example, at a power plant or from an industrial process
- The enhancement of the net oceanic uptake from the atmosphere, for example, through iron fertilization

The DOE Center for Research on Ocean Carbon Sequestration (DOCS)

- Established July 1999
- Centered at LBNL and LLNL
- Participants
  - Eric Adams MIT
  - Jim Barry MBARI
  - Jim Bishop **DOCS Scientific Co-director** LBNL
  - Ken Caldeira **DOCS Scientific Co-director** LLNL
  - Sallie Chisholm MIT
  - Kenneth Coale Moss Landing Marine Laboratory
  - Russ Davis Scripps Institution of Oceanography
  - Paul Falkowski Rutgers
  - Howard Herzog MIT
  - Gerard Nihous Pacific International Center for High Technology Research
  - Terry Surles **DOCS Executive Coordinator** California Energy Commission
  - Bernhardt Trout MIT

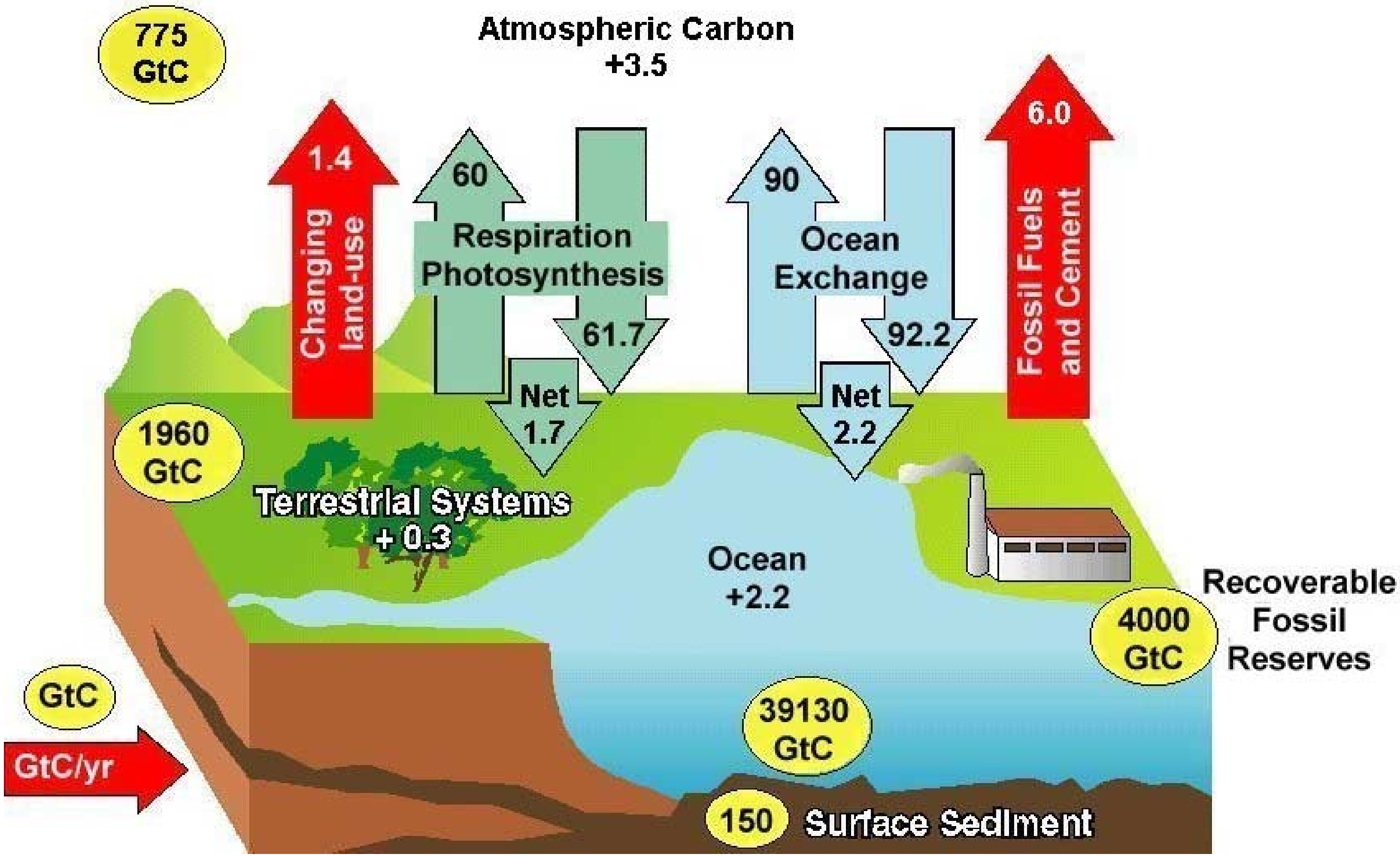
Ocean Carbon Sequestration Options



Ocean Sequestration

- Largest Sink
  - Atmosphere = 750 GtC
  - Terrestrial = 2,200 GtC
  - Ocean = 40,000 GtC
- Atmosphere-Ocean Flux about 90 GtC
- Most carbon released in the atmosphere today will end up in the ocean

Global Carbon Cycle



Maximum Sequestration Rates

- Direct injection
  - Limited by availability of near-coastal CO_2 point sources
  - 15 to 20 % of total fossil-fuel use
- Ocean fertilization
  - Limited by biological transport and ocean mixing rates
  - Perhaps ~1 GtC / yr increase in net ocean carbon uptake could be sustained for hundreds of years (very uncertain)

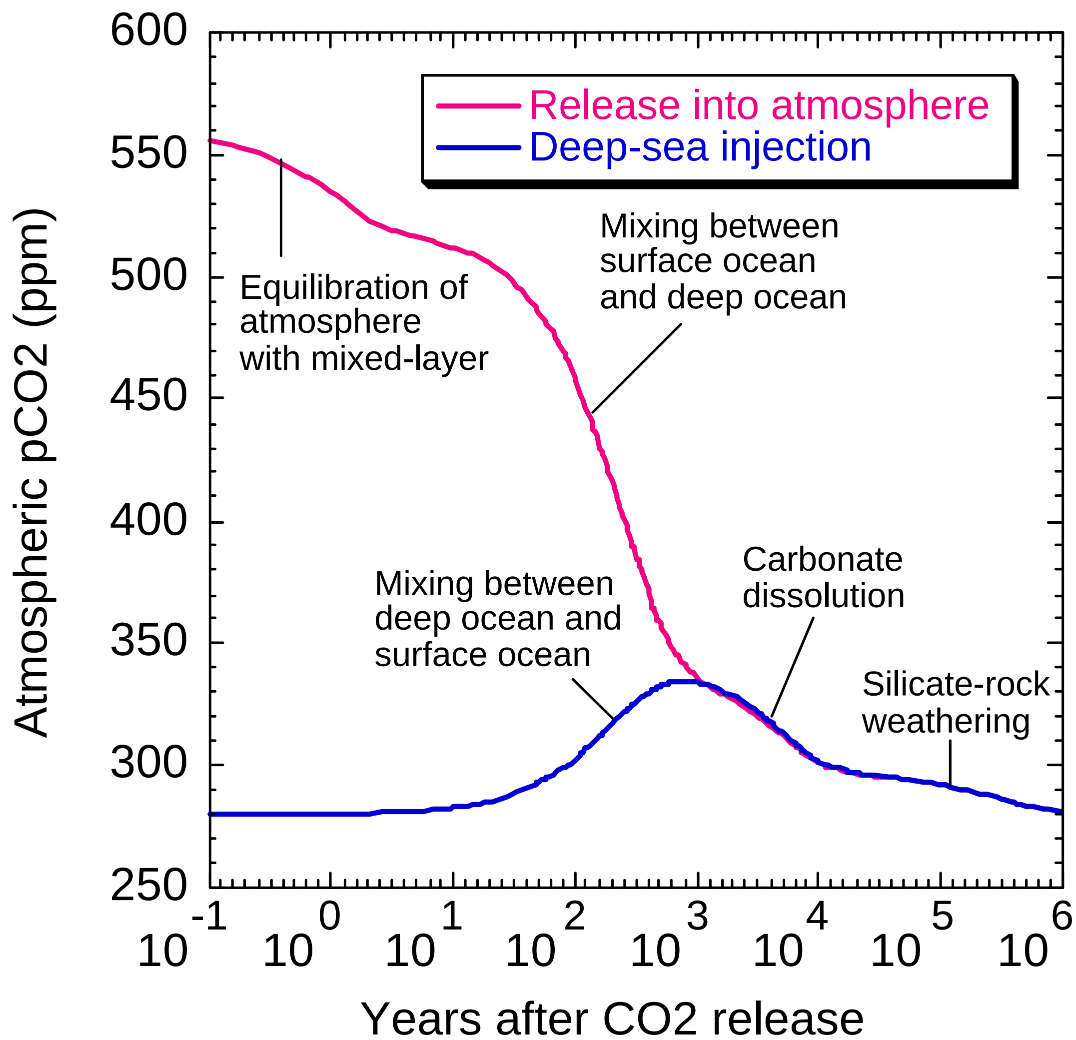
Comparison of Methods

- Direct injection
  - Pros
    - Effective at sequestering CO_2 for hundreds of years
    - Based on proven technologies
    - Strategies can be developed (e.g., carbonate dissolution) to enhance effectiveness and diminish adverse environmental consequences
  - Cons
    - Consumes energy, expensive
    - Suitable only for point sources with access to ocean waters
    - Possible environmental consequences (e.g., pH effects)
- Ocean fertilization
  - Pros
    - Relative inexpensive
    - Simple technologically
    - May improve fishery yields
  - Cons
    - Effectiveness not proven
    - Possible environmental consequences (e.g., ecosystem disturbance)
    - Sequestration rate limited to ~1 PgC / yr

Direct CO_2 Injection Basic rationale

- About 80% of CO_2 emissions will eventually reside as dissolved inorganic carbon in the deep ocean
- Natural transit of this fossil-fuel carbon to the deep ocean-atmosphere is limited by ocean transport processes
  - Ocean mixing time-scale is ~300 yr
- Bypass slow natural ocean mixing by directly injecting fossil-fuel CO_2 into the deep ocean
  - CO_2 would be separated, for example, from power plant flue gases

Rationale



Release into atmosphere
Deep-sea injection
Equilibration of atmosphere with mixed-layer
Mixing between surface ocean and deep ocean
Mixing between deep ocean and surface ocean
Carbonate dissolution
Silicate-rock weathering
Atmospheric pCO2 (ppm)
600
550
500
450
400
350
300
250
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Years after CO2 release

Inorganic sinks for CO_2 emissions to the atmosphere

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

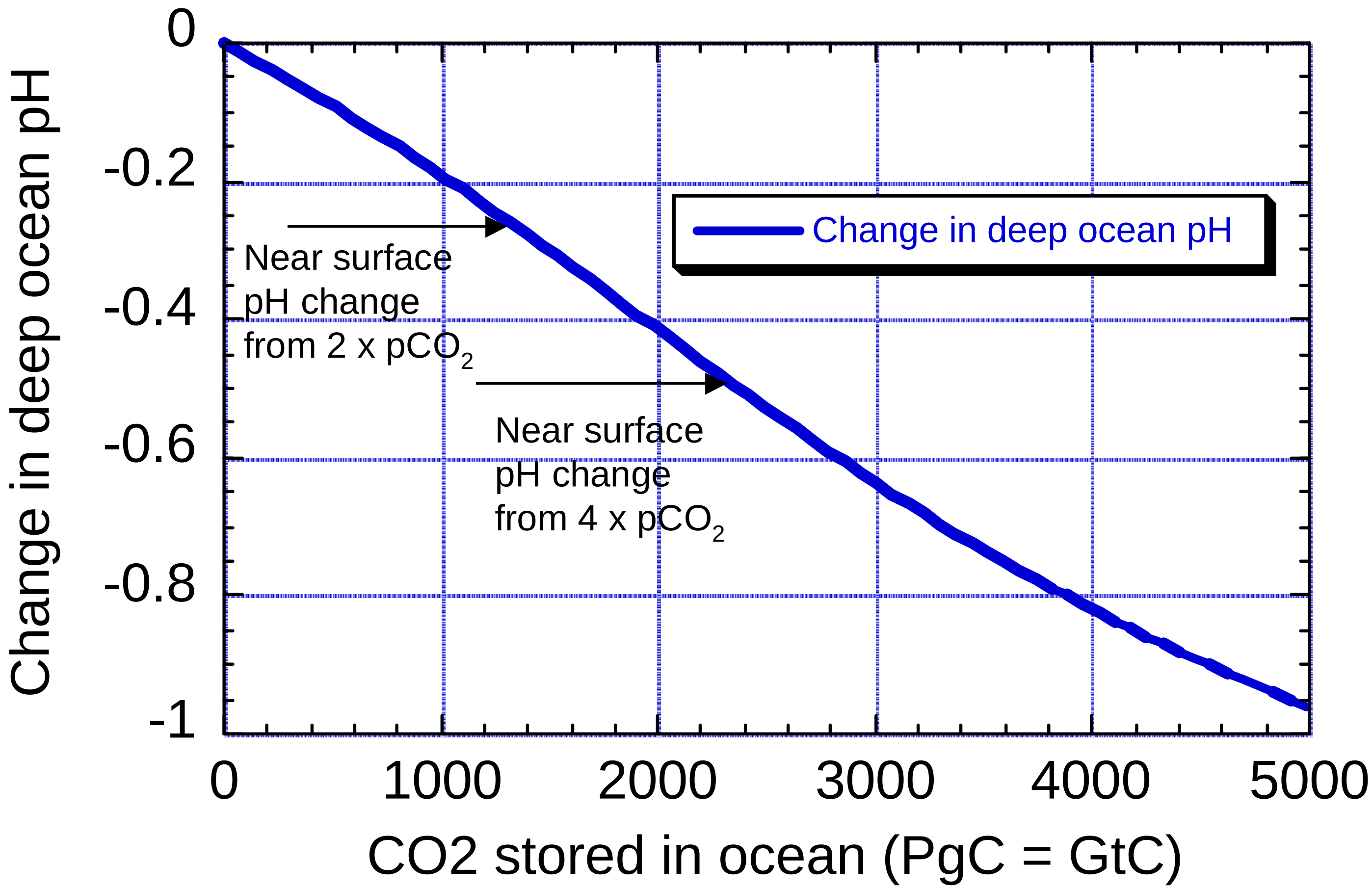
Direct Injection Topics

- Capacity
- Effectiveness
- Injection Methods
- Local Environmental Impacts
- Research activities
  - Modeling
  - Hawaii Experiment
  - Hydrates

Capacity

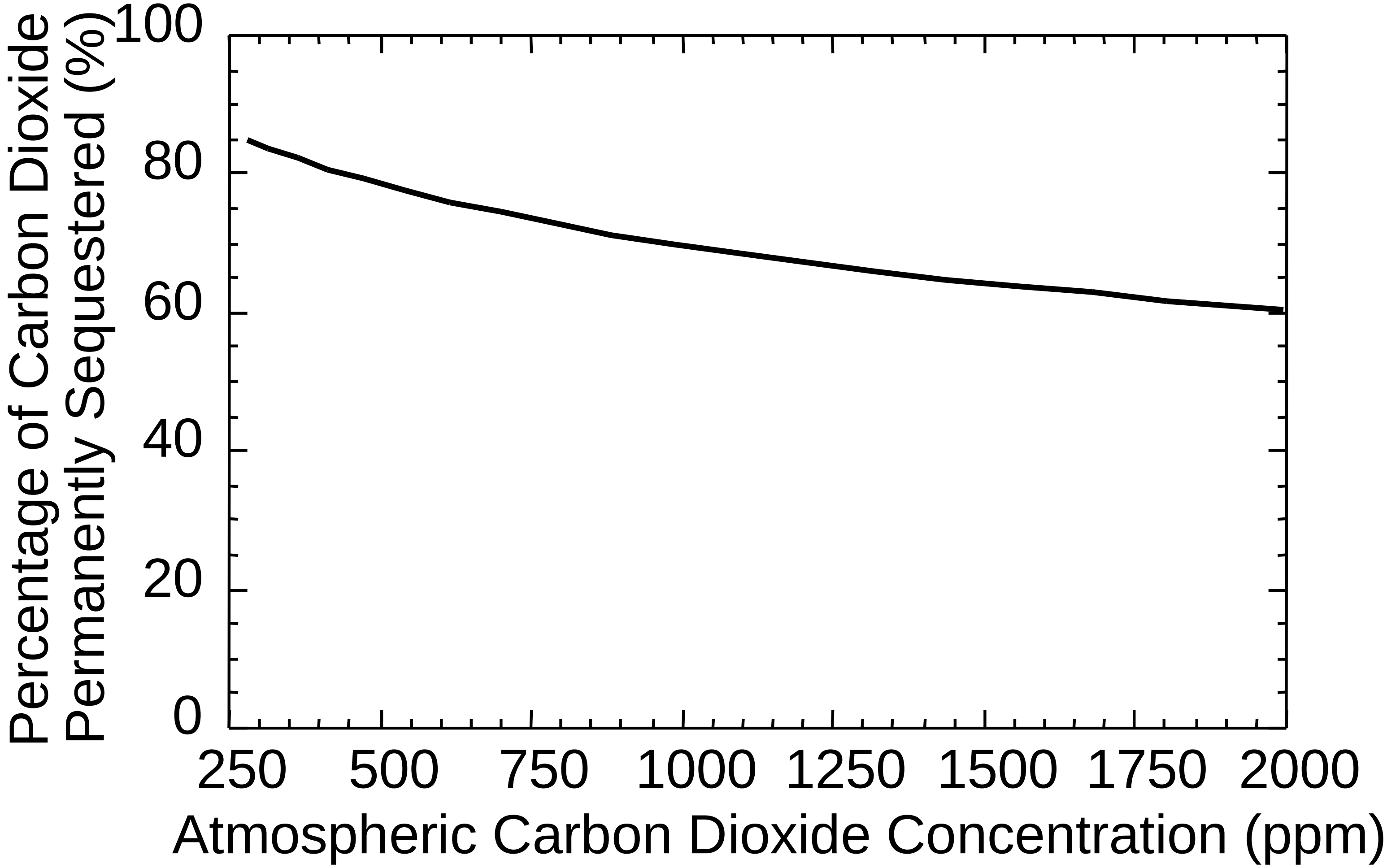
- Based solely on physical view, larger than fossil reserve of 5,000 - 10,000 GtC.
- Based on environmental view, uncertain. For example, sequestering 1300 GtC would change pH by 0.3 units.
- Ocean currently sequestering 2-3 GtC annually.

Capacity

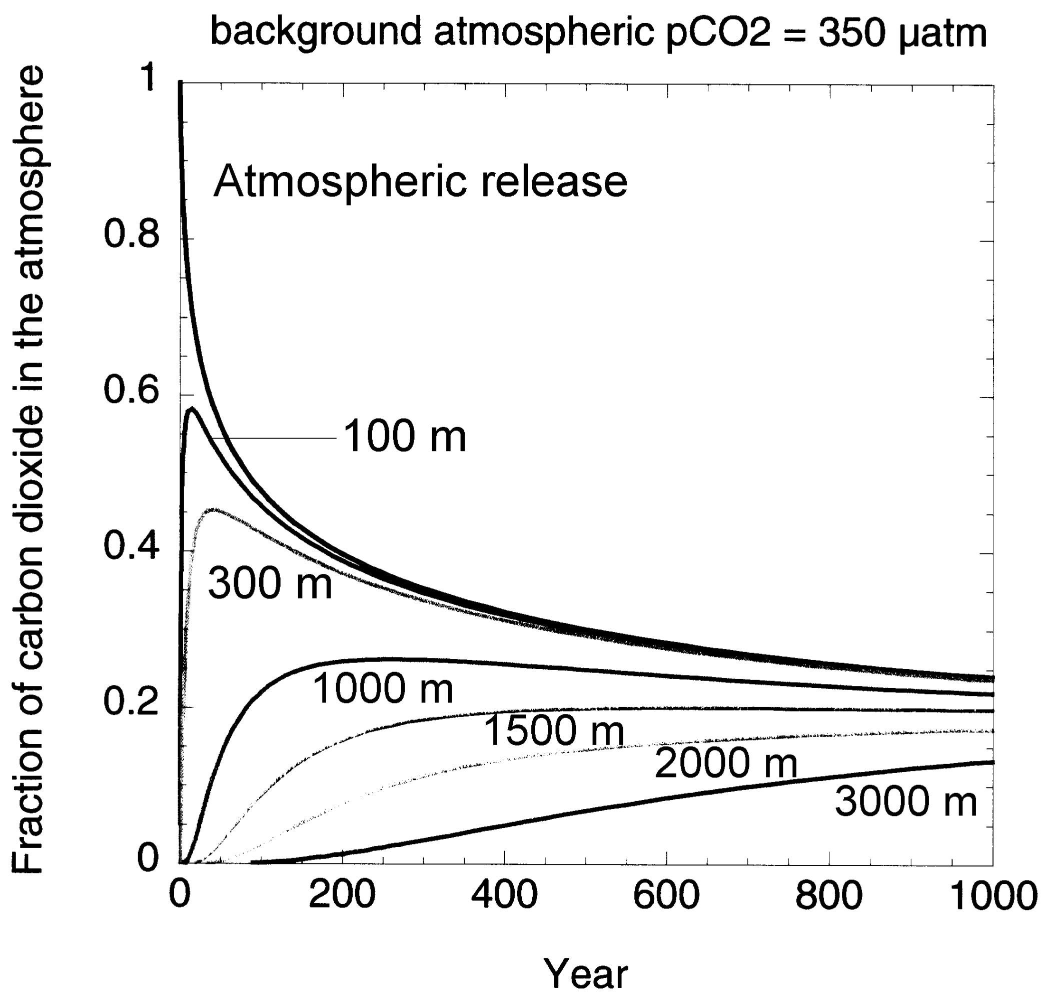


0
-0.2
-0.4
-0.6
-0.8
-1
Change in deep ocean pH
0
1000
2000
3000
4000
5000
CO2 stored in ocean (PgC = GtC)
Change in deep ocean pH
Near surface
pH change
from 2 x pCO_2
Near surface
pH change
from 4 x pCO_2

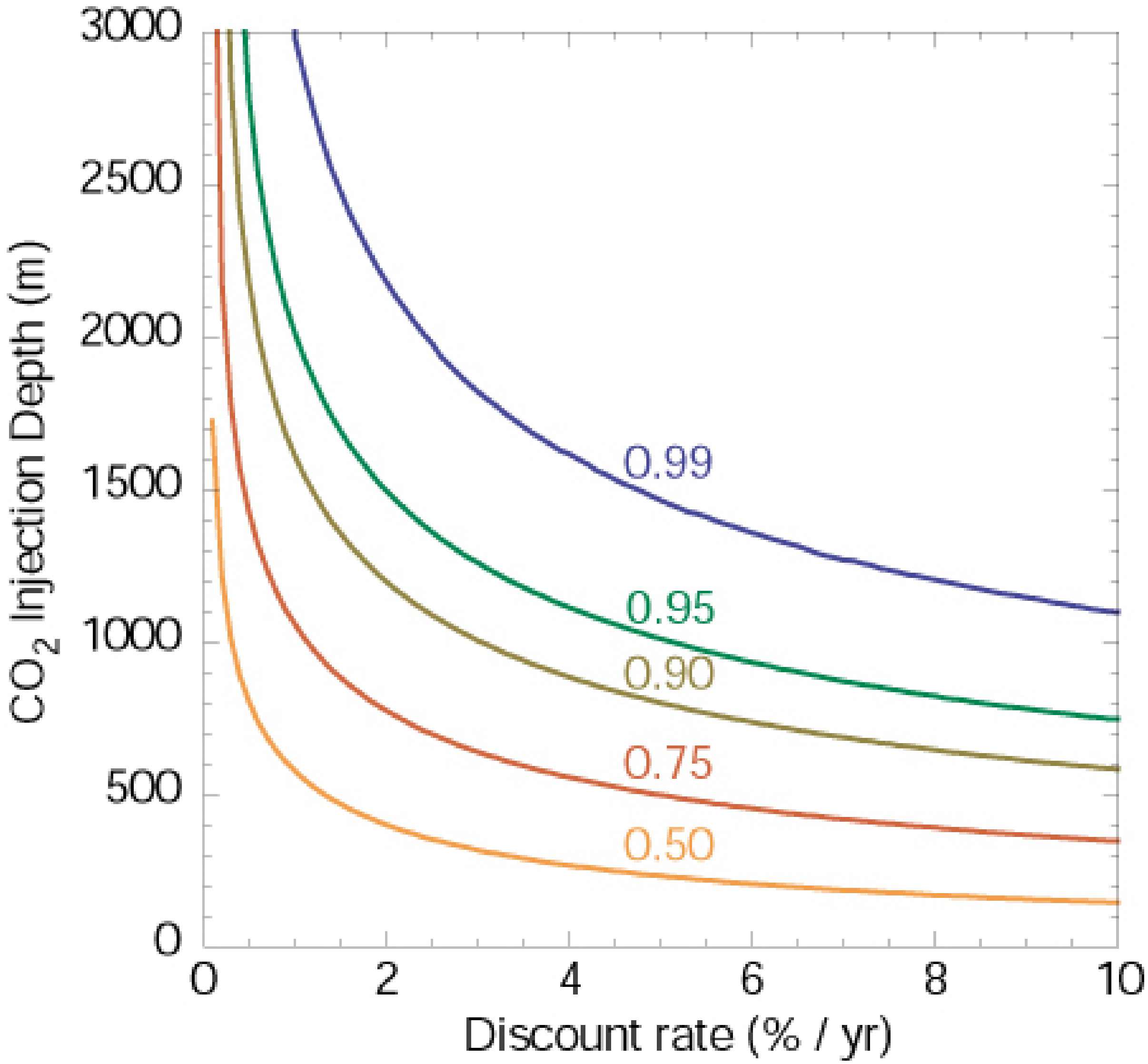
Effectiveness



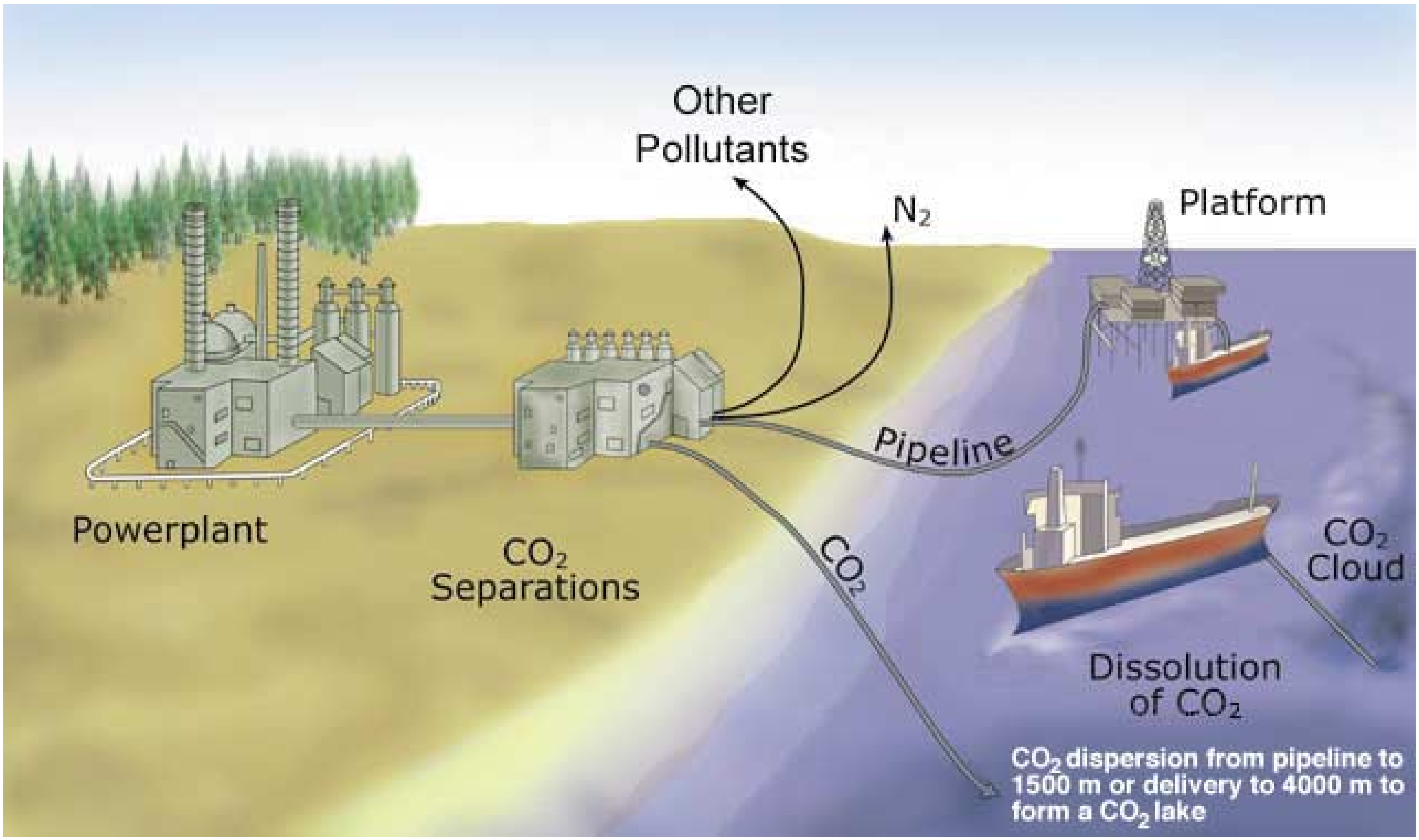
Effectiveness



Effectiveness



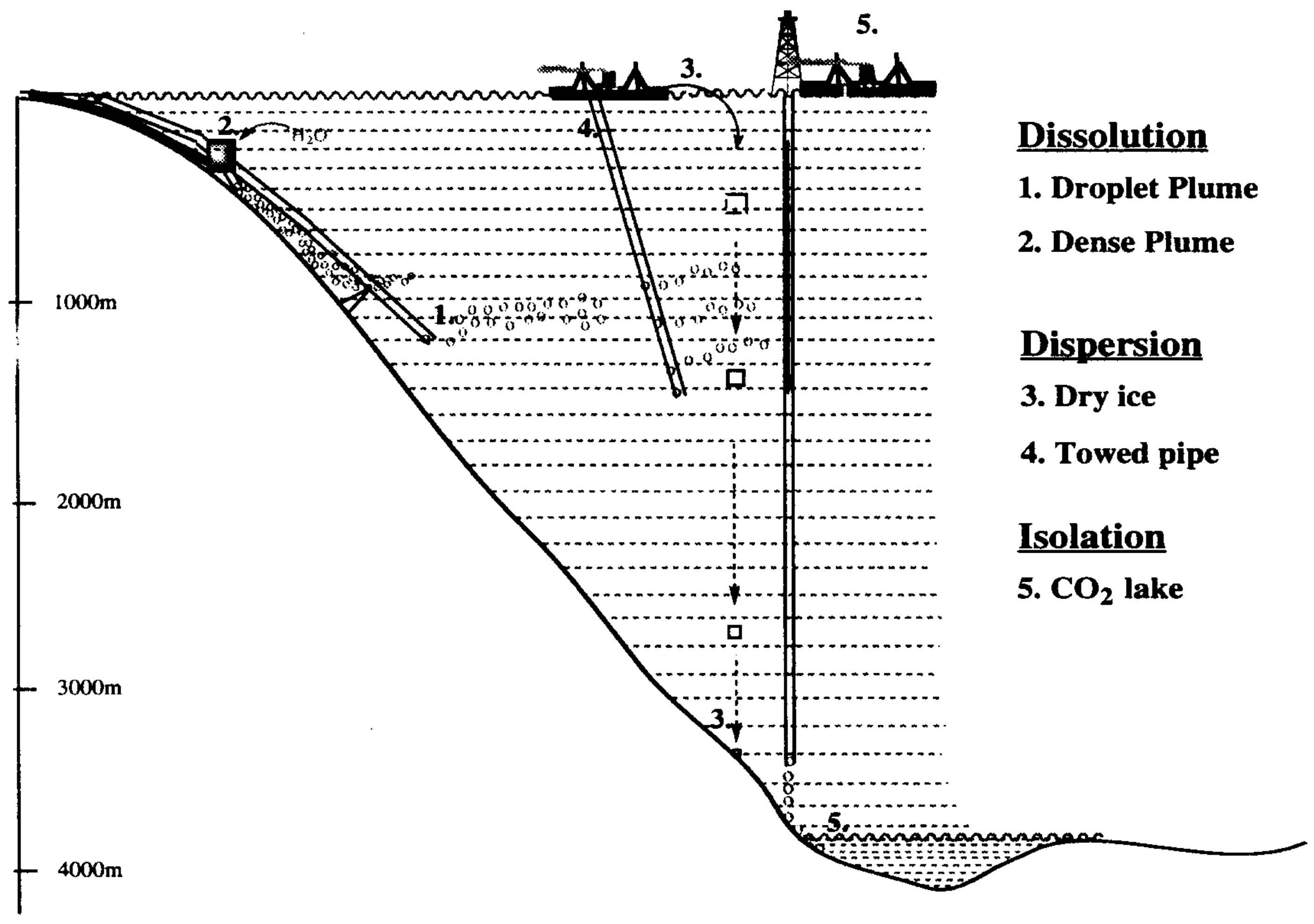
Direct CO_2 injection



Injection Methods

- Ocean Layers
  - Mixed layer (top 100 m)
  - Thermocline (down to 1000 m)
  - Deep ocean
- 10 m depth = 1 bar pressure
- CO_2 Properties
  - Gas, 0-500 m
  - Buoyant liquid, 500-3000 m
  - Denser than seawater, >3000 m
  - Denser than saturated seawater, >3700 m
  - Hydrates, >500 m

Injection Methods



Dissolution

1. Droplet Plume

2. Dense Plume

Dispersion

3. Dry ice

4. Towed pipe

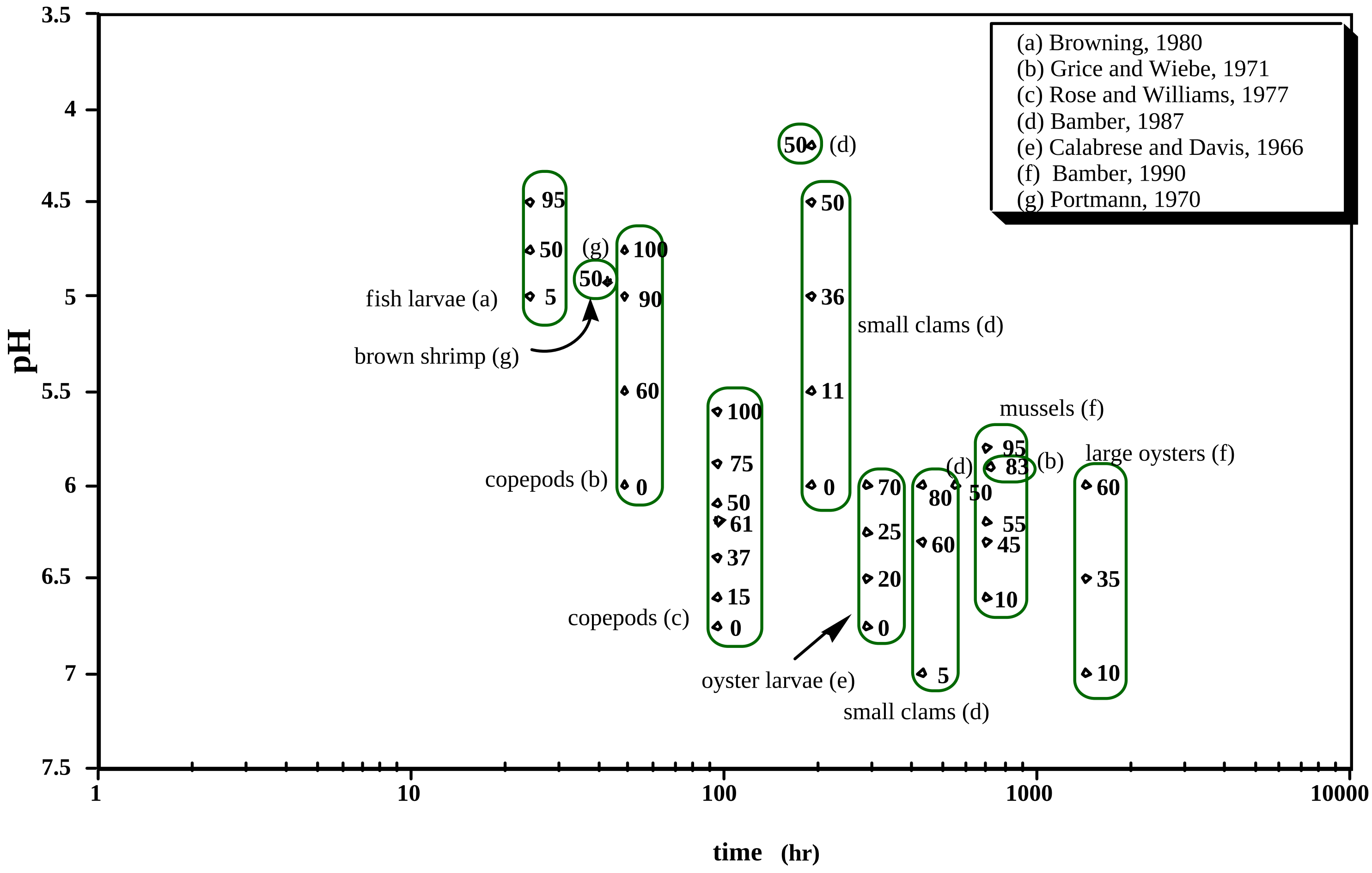
Isolation

5. CO_2 lake

Other Injection Concepts

- Dissolve CO_2 and carbonate minerals in water for sequestration
- Burial of organic carbon in the ocean

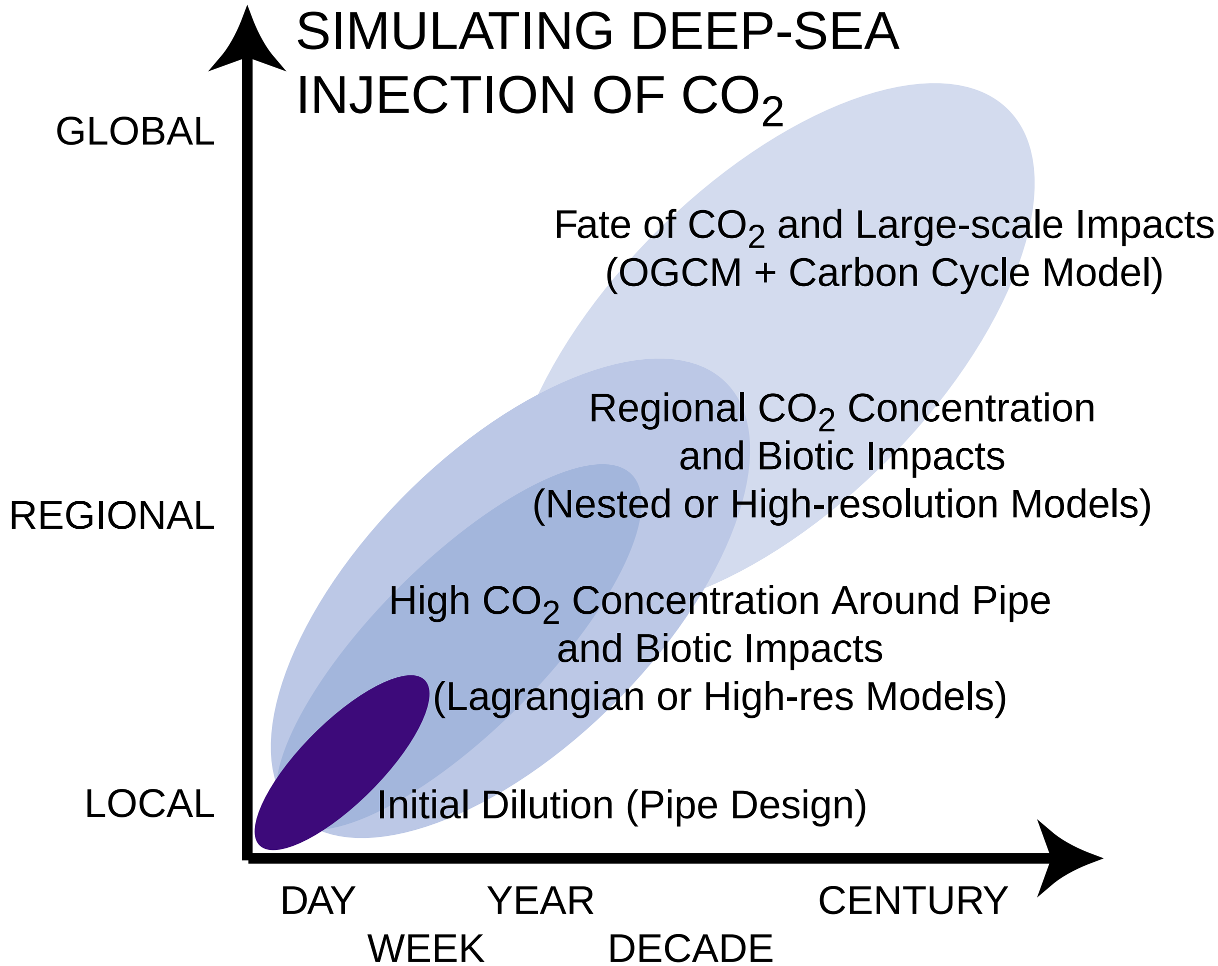
Effects of pH on Marine Organisms



Technology Status

- Most research to date has been theoretical (i.e., modeling) or laboratory-scale experiments
  - Plume modeling
  - Carbon cycle modeling
  - Hydrate studies
  - Environmental impact studies
- Starting in April, 1977, Japan has a national program for CO_2 Ocean Sequestration
- Field experiments starting
  - MBARI
  - International field experiment

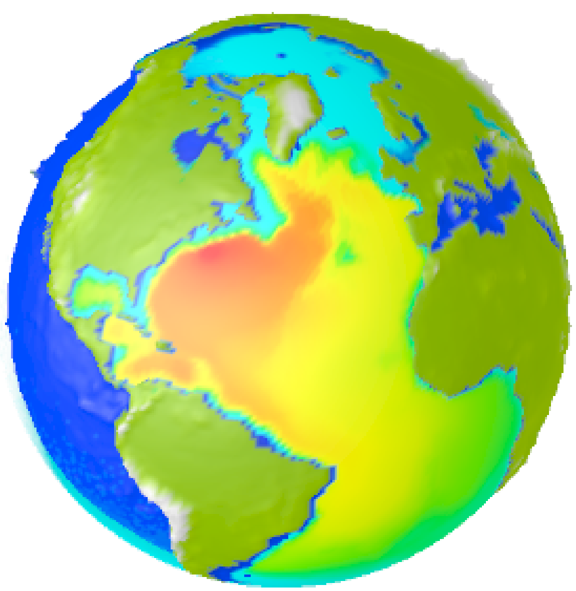
Simulating Direct Injection



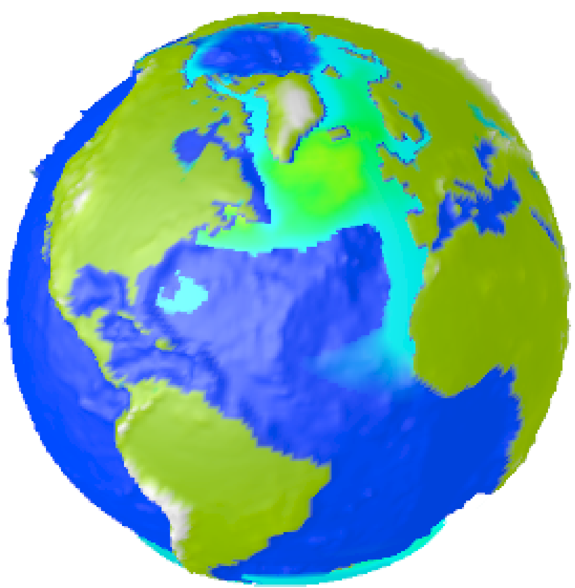
Numerical simulations of ocean carbon sequestration

- Large-scale numerical models of ocean physics and chemistry are being used to simulation ocean carbon sequestration
- Injection off New York at 3000 m depth shown after 100 years of injection of 0.1 PgC / yr

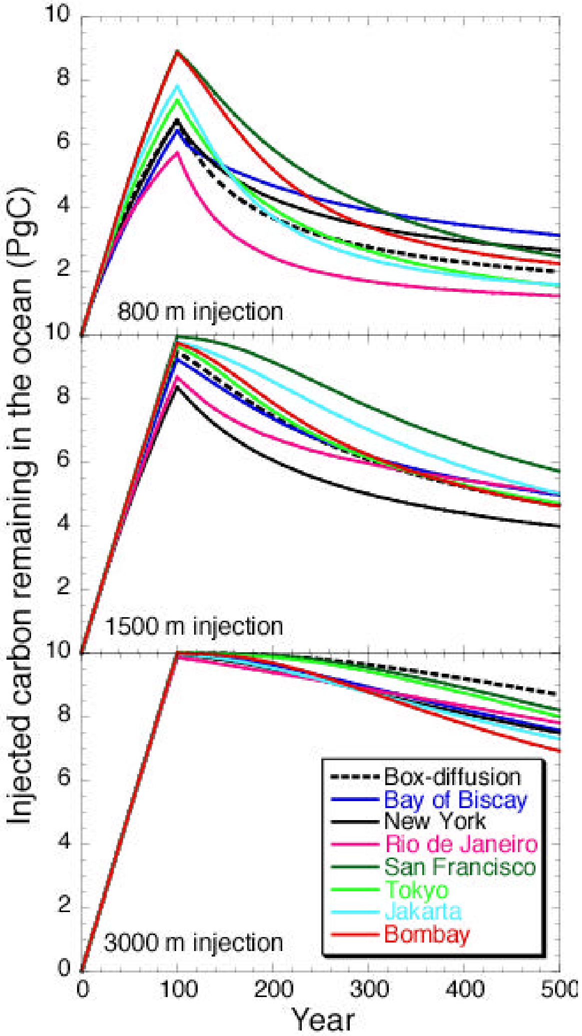
Column inventory



Surface Fluxes



Numerical simulations with an Ocean General Circulation Model



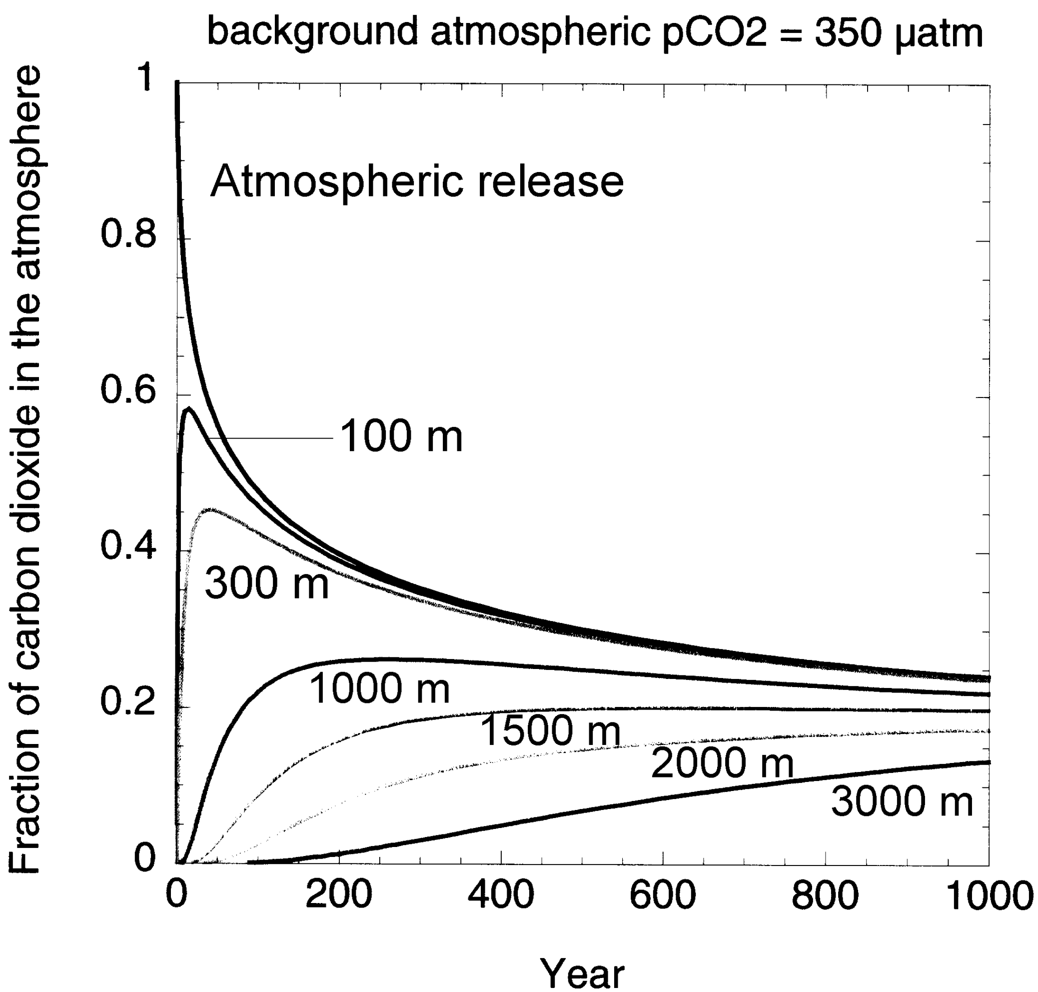
At 800 m depth, ~25 % of injected CO_2 remains in the ocean at least 500 years.

At 1500 m depth, ~50 % of injected CO_2 remains in the ocean at least 500 years.

At 3000 m depth, ~80 % of injected CO_2 remains in the ocean at least 500 years.

About 80 % of the CO_2 that leaks out of the ocean will eventually be reabsorbed by the ocean.

Effectiveness



International Experiment of CO_2 Ocean Sequestration

- Investigate direct injection of CO_2 into the ocean at mid-depth (500-3000 m)
  - Plume physics (rise height, peeling process)
  - CO_2-seawater chemistry (hydrate formation, CO_2 dissolution rates)
  - Perturbations (pH changes)
  - Biological and ecological impacts

Timeline

- December 1997 - Agreement signed
- August 1999 - First survey cruise
- October 2000 – Second survey cruise
- November 2001 – Field experiment

Sponsoring Countries

- Original signatories
  - Japan
  - Norway
  - United States
- Added members
  - Australia
  - Canada
  - Switzerland (ABB)

San Antonio Tank Experiment

5 mm nozzle
fast discharge

5 mm nozzle
slow discharge

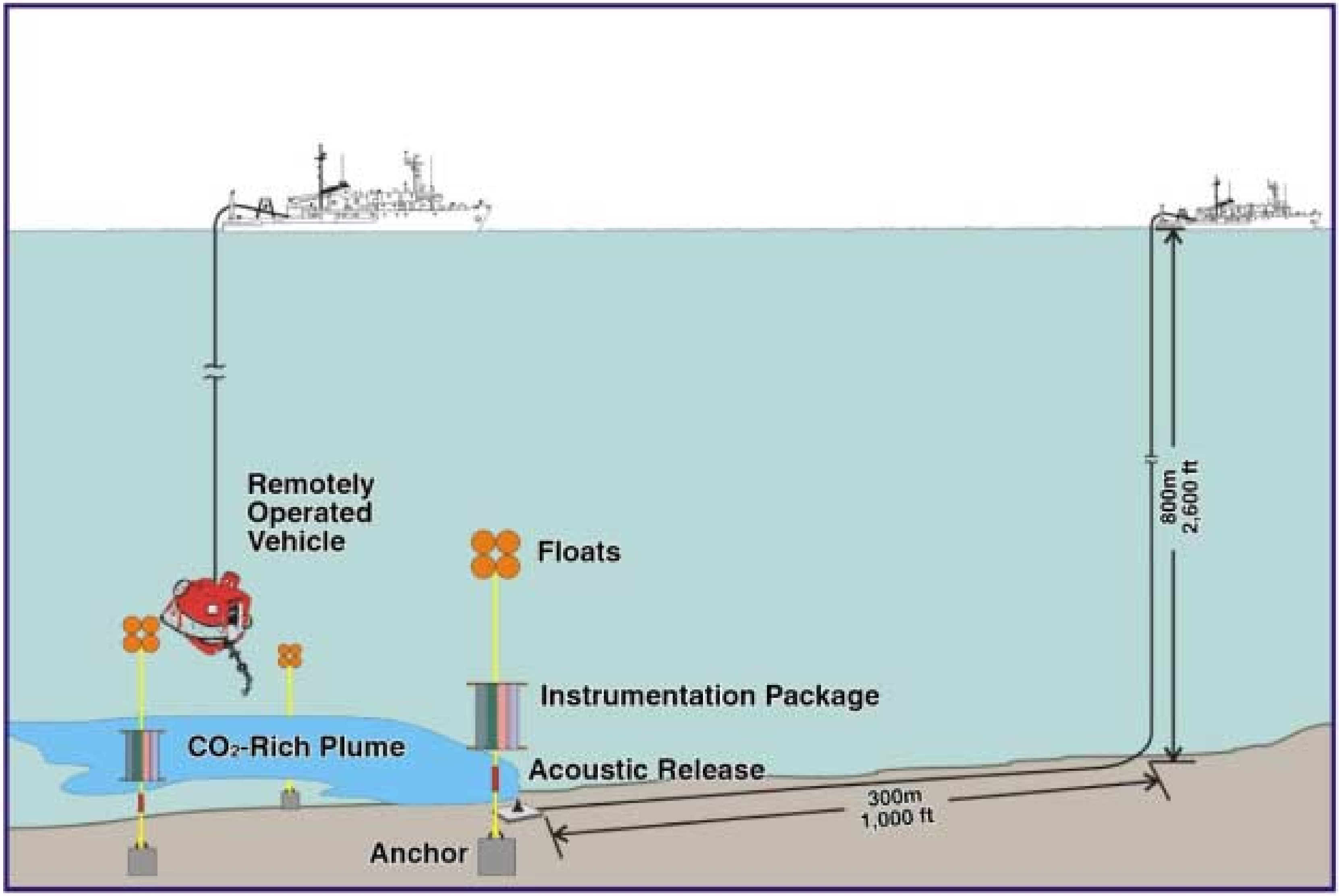
2 mm nozzle
fast discharge

2 mm nozzle
slow discharge

Field Experiment Design

- Diffuser tethered to supply ship
- Release depth at 800 m
- Two flow rates (0.1 kg/s and 1 kg/s)
- Two diffusers (droplet sizes <0.1 to 1 cm)
- Measurements
  - Moored instruments (pH, ADCP, hydrophone)
  - ROVs (video, salinity, T, pH, ADV, water samples)
  - CTD/bottle casts
  - Benthic samples

Experimental Setup



Challenges

- Infrastructure
  - CO_2 flow control
  - Hydrate blockage
  - Depressurizing pipe
- Measurements
  - Choice of a suitable tracer
  - Performing a full 3D survey in rapidly changing current

Permitting and Public Outreach

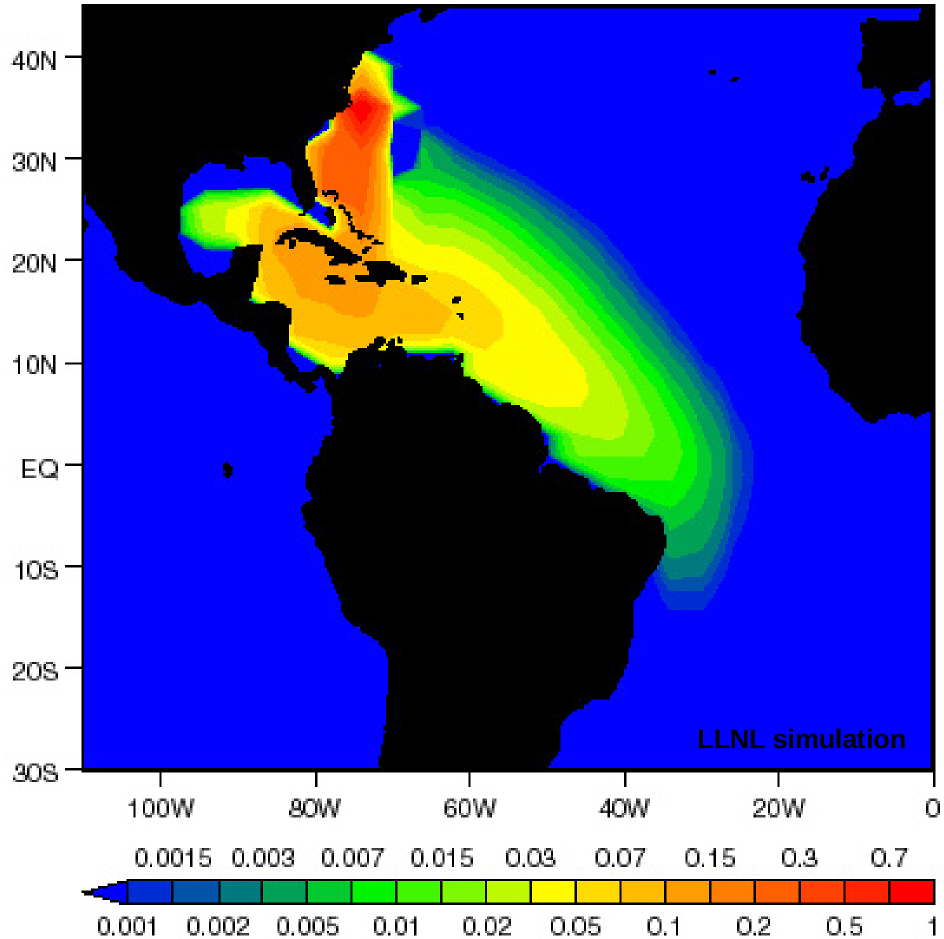
- Federal Environmental Assessment (EA) approved
- Water Quality Permit from EPA still required
- Public Outreach program in place
- Significant opposition for a variety of reasons

Hydrate Discussion

Direct CO_2 injection

- Science and technology gaps
  - Optimizing injection strategy
  - Engineering issues
  - Predicting effectiveness
  - Environmental impacts

- Address gaps through
  - Experiments
  - Observations
  - Modeling
  - Monitoring and verification technology development



Relative concentration
at injection depth = 1700 m

Research Needs

- Better information on biological impacts
- Larger scale CO_2 release experiments with an emphasis on evaluation of biotic impacts
- Modeling on the scale of 100's of meters to 100's of kilometers.
- Educate stakeholders and the public so they can make informed decisions

Web Sites

- CO_2 Experiment:
  - http://www.co2experiment.org/
- DOCS
  - http://esd.lbl.gov/DOCS/

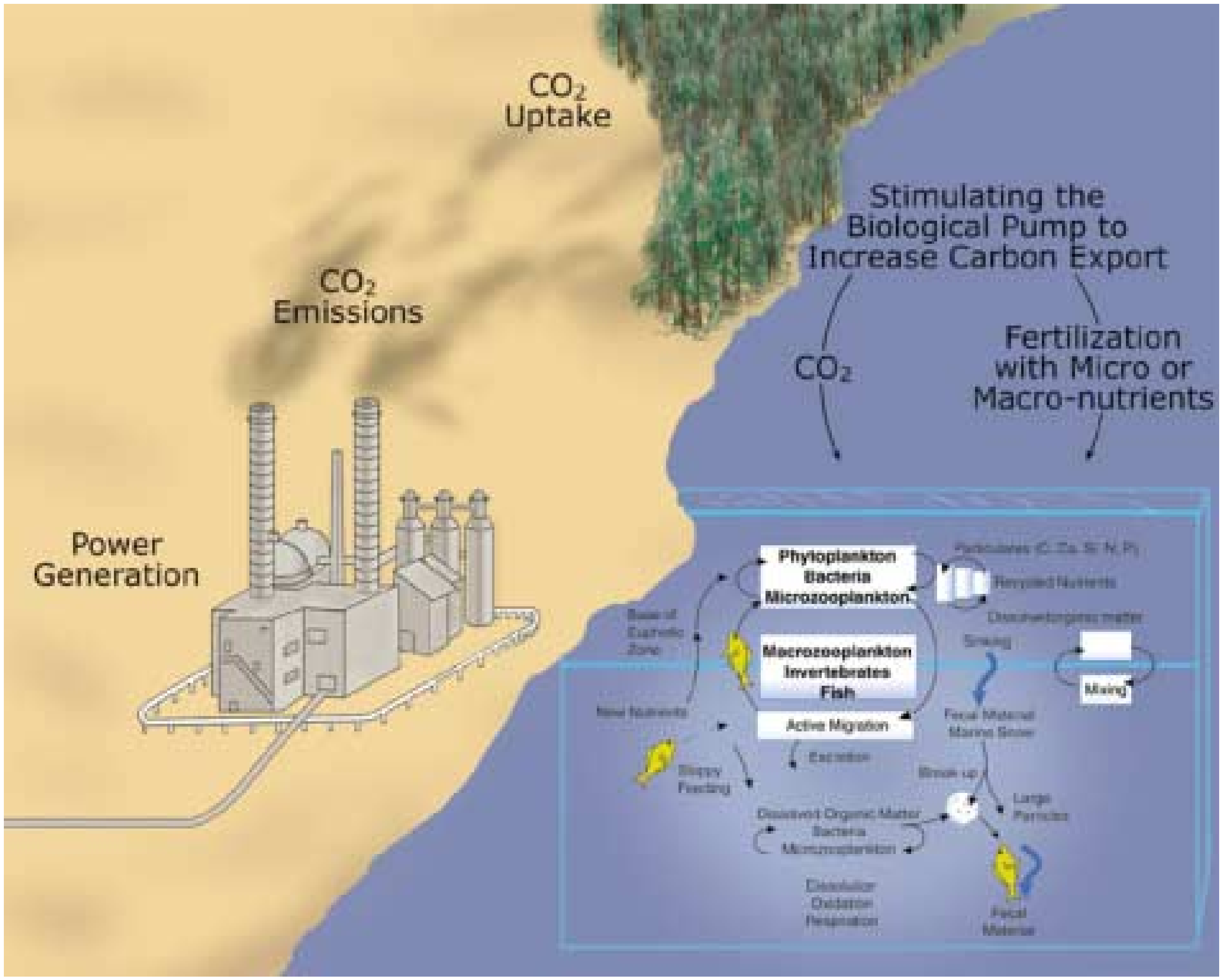
Ocean fertilization

- 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.
- Research questions (selection)
  - To what extent do various nutrients limit export production?
  - How can we monitor the effects of ocean fertilization?
  - What unintended impacts would occur as a result of fertilization?
  - To what extent would fertilization increase export production?
  - To what extent would increased export production increase CO_2 uptake by the ocean?
  - How deeply will the exported carbon remineralize in the ocean?
  - How long will the remineralized CO_2 remain in the ocean?

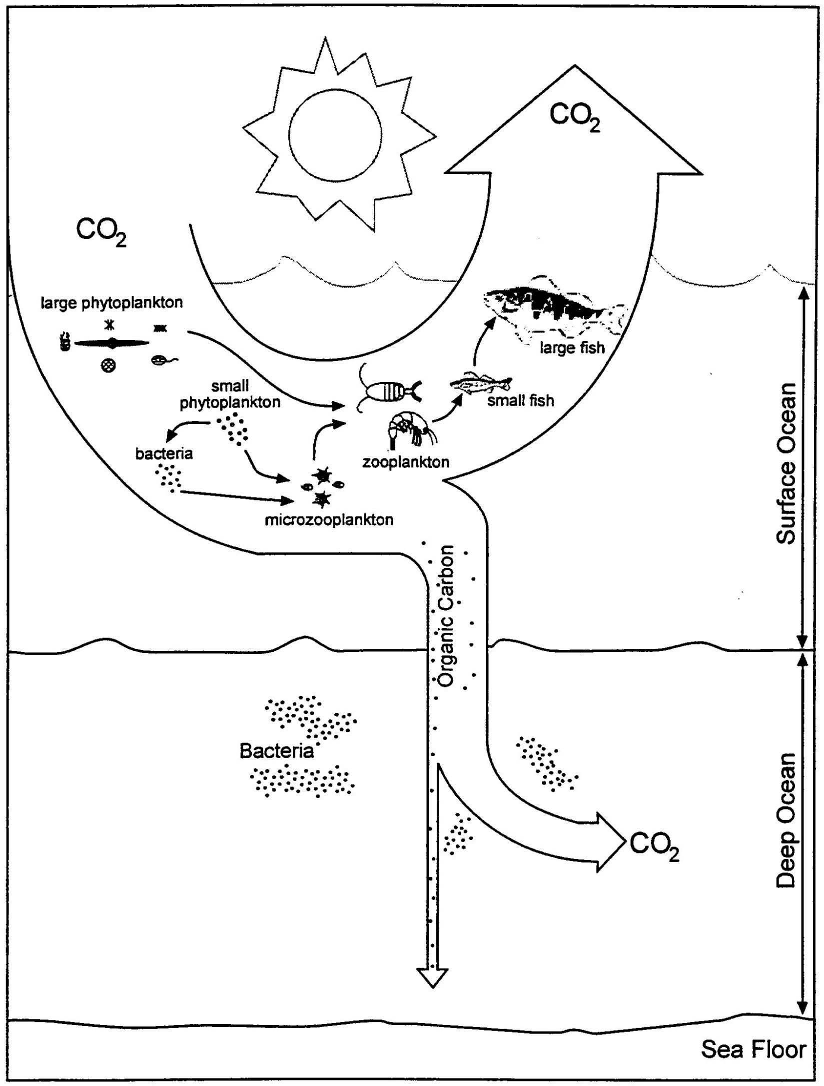
Ocean fertilization: Basic rationale

- About 80% of CO_2 emissions will eventually reside as dissolved inorganic carbon in the deep ocean
- Marine organic matter falls from the surface ocean to the deep ocean, transporting carbon away from the atmosphere
- In much of the ocean, this biological transport may be limited by the availability of micronutrients such as iron
- Bypass slow natural ocean mixing by fertilizing the surface ocean, thus enhancing the biological flux of carbon to the deep ocean

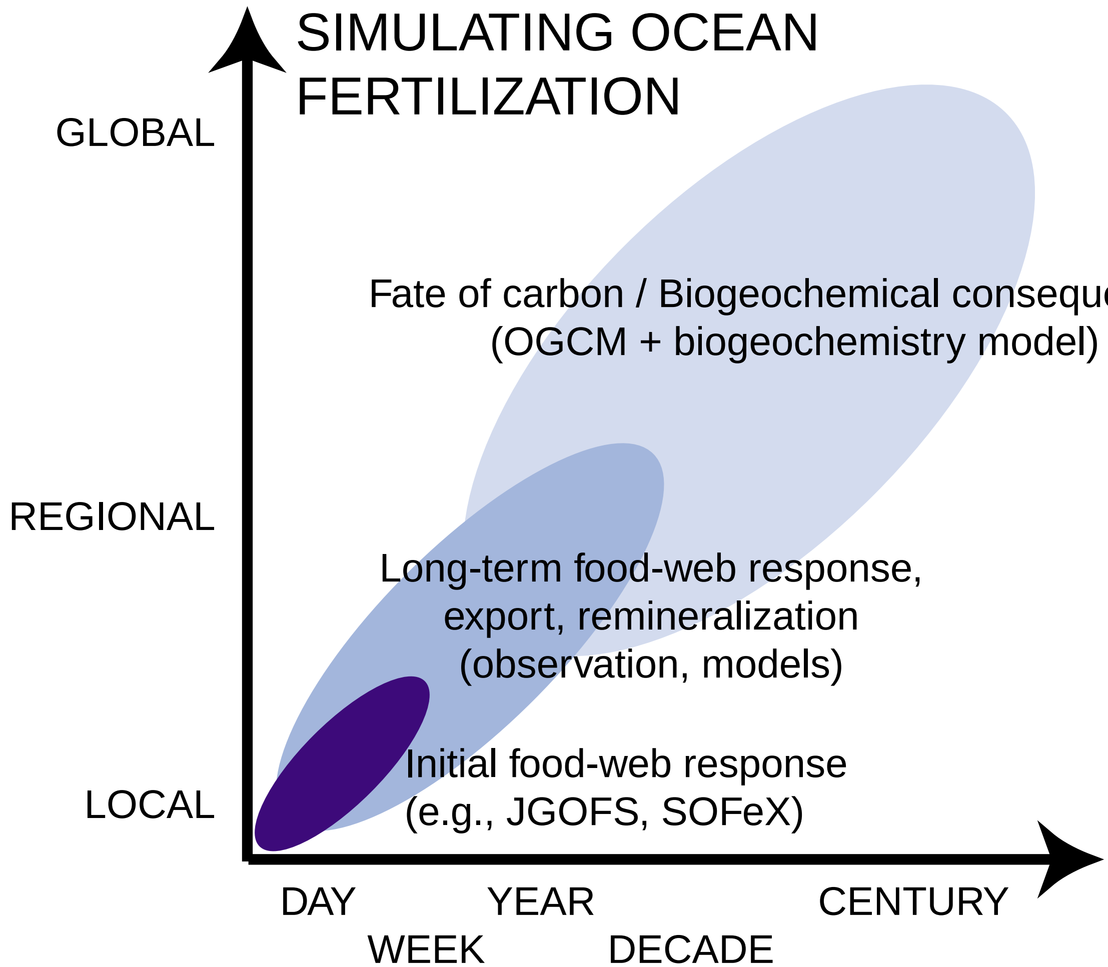
Ocean fertilization



Enhancement of Natural Carbon Sequestration

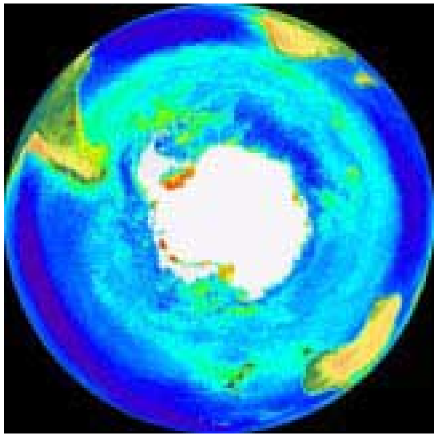


Simulating ocean fertilization



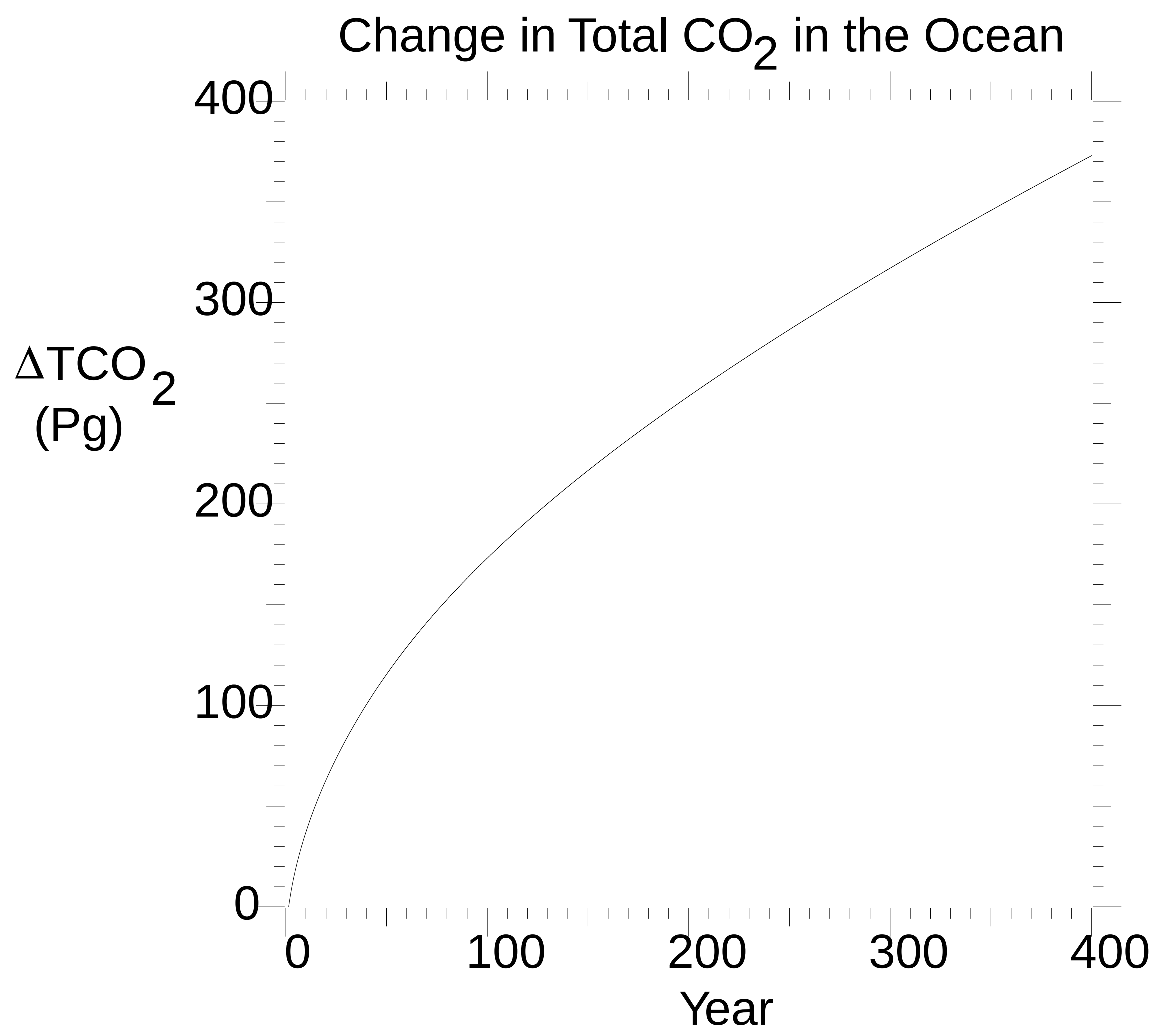
Science and technology gaps: Fertilization

- Gaps
  - Understanding long-term effects on marine ecosystems, e.g., food-chain effects
  - Understand impacts on natural biogeochemical cycles, e.g., ocean anoxia
  - Understand factors affecting long-term effectiveness, e.g., remineralization length
  - Understanding the natural carbon cycle, e.g., factors controlling export production



- Address these gaps through
  - Experiments
  - Observations
  - Modeling
  - Monitoring and verification technology development

Southern Ocean fertilization simulations



Summary

- Ocean is large potential sink for CO_2
- Much research to be done
  - Engineering analysis
  - Environmental assessment
  - Ocean circulation modeling
  - Public outreach
- Several significant efforts underway
- The journey is just beginning