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

Carbon management

- Diminish end-use demand
- Decarbonate energy supply
- Sequester CO₂
  - Geologic storage
  - Land biosphere storage
  - Ocean storage
Global carbon cycle

yr ~1990

\[ \text{pCO}_2 = 354.9 \text{ ppm} \]
Atmospheric CO₂ content

Mauna Loa Monthly Mean Carbon Dioxide

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) 497-5678, ptaus@aml.noaa.gov, and Dr. Charles D. Keeling, SIO, La Jolla, California, (858) 534-6801, cdkeling@ucsd.edu
Inferred temperature anomalies
Ocean sequestration options

Ocean storage

Ocean fertilization
- LNLC options
- HNLC options

Direct CO$_2$ injection
- Mid-depth options
- Lake or seafloor options

Other options
- e.g., Carbonate dissolution
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

- **CO₂ absorption by surface ocean**
  - ~1 yr
  - \( \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}^+ + \text{HCO}_3^- \)

- **Mixing to deep ocean**
  - ~300 yr

- **Carbonate dissolution**
  - ~6000 yr
  - \( \text{CO}_2 + \text{CaCO}_3 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \)

- **Silicate-rock weathering**
  - ~300,000 yr
  - \( \text{CO}_2 + \text{CaSiO}_3 \rightarrow \text{CaCO}_3 + \text{SiO}_2 \)
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?
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

\[ \Delta TCO_2 \text{ (Pg)} \]

Change in Total CO\(_2\) in the Ocean

Year

0 100 200 300 400
Southern Ocean fertilization simulations

Change in Export Production and Net Flux of CO₂ into the Ocean

Pg/yr

Year

Air to Sea CO₂ Flux

△Export Production
Southern Ocean fertilization simulations

![Graph showing Air to Sea Flux of CO₂ over time. The graph plots Flux (Pg/yr) against Year.]
Southern Ocean fertilization simulations
Effect of fertilizing entire ocean south of 30°S for one year
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

- Powerplant
- CO$_2$ Separations
- Other Pollutants
- N$_2$
- Pipeline
- CO$_2$
- Dissolution of CO$_2$

CO$_2$ dispersion from pipeline to 1500 m or delivery to 4000 m to form a CO$_2$ lake
Deep-sea CO₂ injection

- Direct CO₂ injection has been proposed as an effective means of
  - diminishing future climate change
  - with minimal economic and environmental damage
Direct CO₂ injection into the ocean interior can slow the accumulation of CO₂ 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 CO₂ injection
Comparison of 3D and 1D models at 3000 m depth
Direct CO₂ 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
Carbon removal processes

- **CO₂ absorption by surface ocean**
  - ~1 yr
  - \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}^+ + \text{HCO}_3^- \]

- **Mixing to deep ocean**
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- **Silicate-rock weathering**
  - ~300,000 yr
  - \[ \text{CO}_2 + \text{CaSiO}_3 \rightarrow \text{CaCO}_3 + \text{SiO}_2 \]
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$_2$O $\rightarrow$ H$^+$ + HCO$_3^-$
  - use this carbonic acid to dissolve crushed limestone
    - H$^+$ + HCO$_3^-$ + CaCO$_3$ $\rightarrow$ 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

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<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
<th>(D)</th>
<th>(E)</th>
<th>(F)</th>
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<td>seawater</td>
<td>in equil.</td>
<td>in equil.</td>
<td>degassed</td>
<td>diluted</td>
<td>degassed</td>
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<tr>
<td>with atm CO₂</td>
<td>with 0.15 atm CO₂</td>
<td>with 0.15 atm CO₂</td>
<td>to seawater</td>
<td>with seawater</td>
<td>to equil.</td>
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<tr>
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<td>150000</td>
<td>35339</td>
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<td>2314</td>
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<td>5143</td>
<td>1212</td>
<td>14</td>
<td>12</td>
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<tr>
<td>HCO₃⁻ (µmol/kg)</td>
<td>1844</td>
<td>2315</td>
<td>14749</td>
<td>14563</td>
<td>1983</td>
<td>1928</td>
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<td>CO₃²⁻ (µmol/kg)</td>
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<td>1</td>
<td>29</td>
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<tr>
<td>Ca²⁺ (mmol/kg)</td>
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<td>10.12</td>
<td>16.37</td>
<td>16.37</td>
<td>10.18</td>
<td>10.18</td>
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<tr>
<td>Ω_{Calcite}</td>
<td>4.14</td>
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<td>1.00</td>
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<td>ffCO₂/CaCO₃ dissolved</td>
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<td>1.22</td>
<td>1.22</td>
<td>0.66</td>
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</table>

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

- Release into atmosphere
- Deep-sea injection
- Carbonate-dissolution method

Years after CO2 release:
- 0
- 1000
- 2000
- 3000
- 4000
- 5000

Atmospheric pCO2 (ppm):
- 280
- 320
- 360
- 400
- 440
- 480
- 520
- 560

Carbonate-dissolution method
Carbonate-dissolution method

![Graph showing atmospheric pCO2 (ppm) over years after CO2 release.]

- **Graph Key:**
  - **Pink Line:** Release into atmosphere
  - **Blue Line:** Deep-sea injection
  - **Teal Line:** Carbonate-dissolution method

**Legend:***
- **Degassing of excess CO2(aq)**
- **Re-absorption into ocean and mixing to deep ocean**
- **Silicate-rock weathering**

**Axes:**
- **Y-axis:** Atmospheric pCO2 (ppm)
- **X-axis:** Years after CO2 release

**Description:**
- The graph illustrates the atmospheric pCO2 (ppm) over time, following the release of CO2 into the atmosphere.
- The pink line represents the release into the atmosphere, showing a sharp decrease in pCO2.
- The blue line, representing deep-sea injection, shows a less pronounced decrease in pCO2.
- The teal line, representing the carbonate-dissolution method, illustrates a gradual decrease in pCO2, indicating the process of re-absorption into the ocean and mixing to the deep ocean.
- Silicate-rock weathering is shown as a separate process, indicated by a separate line.
Carbonate-dissolution increases long-term effectiveness of carbon sequestration
Carbonate-dissolution method: Costs

- Estimated cost per tonne CO\textsubscript{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\textsuperscript{4} m\textsuperscript{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\textsubscript{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 $< 1 \text{ PgC} / \text{yr}$

- **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