Joint MCRN/IMA Math and Climate Seminar
Tuesdays 11:15 - 12:05
streaming video available at
www.ima.umn.edu
A report on “Glacial/interglacial variations in atmospheric carbon dioxide,” by Sigman and Boyle

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Seminar on the Mathematics of Climate
School of Mathematics
January 28, 2014
Q: Where does atmospheric carbon go during glacial maxima?

Atmospheric CO$_2$ ~100 ppm lower during glacial maxima
Q: Where does atmospheric carbon go during glacial maxima?

Atmosphere: $\text{CO}_2 = 600 \text{ Pg C}$
$\tau_{(\text{atm.-surf.})} = 10 \text{ yr}$; $\tau_{(\text{atm.-terr.})} = 6 \text{ yr}$

Terrestrial: $C_{\text{org}} = 2,100 \text{ Pg C}$
$\tau_{(\text{atm.-terr.})} = 18 \text{ yr}$

Surface ocean: $\text{DIC} = 700 \text{ Pg C}$
$\tau_{(\text{surf.-deep})} = 25 \text{ yr}$

Export: $C_{\text{org}} = 4 \text{ Pg C yr}^{-1}$
$\text{CaCO}_3 = 1 \text{ Pg C yr}^{-1}$

Deep ocean: $\text{DIC} = 38,000 \text{ Pg C}$
$\tau_{(\text{surf.-deep})} = 1,250 \text{ yr}$

$\text{CaCO}_3$ burial: $0.2 \text{ Pg C yr}^{-1}$

River input of dissolved $\text{CaCO}_3$: $0.2 \text{ Pg C yr}^{-1}$

Sediments and crust:
$(\text{Ca,Mg})\text{CO}_3 = 46,000,000 \text{ Pg C}$
$\tau_{(\text{weathering})} = 240 \text{ Myr}$
$C_{\text{org}} = 15,000,000 \text{ Pg C}$
$\tau_{(\text{weathering})} = 300 \text{ Myr}$

Sigman & Boyle Figure 2
Q: Where does atmospheric carbon go during glacial maxima?
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1) To the land?

- vegetation → ice
- tropical forest → grassland
- spread of deserts
- organic-rich rich continental shelves exposed

\[ \frac{^{13}C}{^{12}C} \text{ ratio in benthic foraminifera: } 0.3-0.4\% \text{ lower during glacial periods} \]

"Source not sink"

Photo © Hans Hillewaert / CC-BY-SA-3.0
Q: Where does atmospheric carbon go during glacial maxima?
Q: Where does atmospheric carbon go during glacial maxima?

② To the colder ocean?

Colder water dissolves more CO₂
Q: Where does atmospheric carbon go during glacial maxima?

To the colder ocean?

Colder water dissolves more CO₂

Sea water freezes at -2 °C

↓ 3-5 °C (low latitude)

↓ < 4 °C

Photo: www.nowpublic.com
Q: Where does atmospheric carbon go during glacial maxima?

2 To the colder ocean?

CYCLOPS model
atmospheric CO₂
↓ 30 ppmv

Not enough
Q: Where does atmospheric carbon go during glacial maxima?
Q: Where does atmospheric carbon go during glacial maxima?

3) Salinity effects?

↑ Glaciers  ↑ Ocean salinity  ↓ Solubility of CO₂

8.5

23.5

↓ 30 p.p.m.v.

Image © by Jeff Silkwood
http://academic.emporia.edu/aberjame/ice/lec01/lec1.htm
Q: Where does atmospheric carbon go during glacial maxima?
Ocean Alkalinity

\[ \text{DIC} \rightarrow \text{CO}_2 \text{(aq)} \rightarrow \text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^- \rightarrow 2\text{H}^+ + \text{CO}_3^{2-} \rightarrow \text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3 \rightarrow \text{ALK} \text{“acid-titrating capacity”} \rightarrow \text{burial} \rightarrow \text{weathering} \]
Q: Where does atmospheric carbon go during glacial maxima?
$Q$: Where does atmospheric carbon go during glacial maxima?
Where does atmospheric carbon go during glacial maxima?

5 Biologically pumped to the ocean interior?
high latitude

inorganic carbon

organic carbon

depth ocean

surface ocean

atm

low latitude

nutrient limited

export production

NOT nutrient limited
inorganic carbon
organic carbon

Redfield ratios: $1 : 16 : 106$

<table>
<thead>
<tr>
<th>Increase in ocean nutrient res.</th>
<th>CaCO$_3$ export</th>
<th>Decrease in atm. CO$_2$ (p.p.m.v.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% proportionate</td>
<td></td>
<td>30-45 $\rightarrow$ 15-25</td>
</tr>
<tr>
<td>30% constant</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>50% constant</td>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>
Redfield ratios
1 : 16 : 106

nitrogen fixation

denitrification

NO$_3^-$
NH$_4^+$
N$_2$

deep ocean
surface ocean
atm
Q: Where does atmospheric carbon go during glacial maxima?

- Low lat. nutrient reservoir:
  - Biologically pumped to the ocean interior:
  - atm. CO2 by 15-80 ppmv
high latitude

*NOT* nutrient limited
HIGH NUTRIENT UTILIZATION

LOW NUTRIENT UTILIZATION

- **nutrients**
- **inorganic carbon**
- **organic carbon**
Nutrient utilization = \frac{\text{Uptake}}{\text{Supply}} = 1 - \frac{[\text{NO}_3^-]_{\text{preformed}}}{[\text{NO}_3^-]_{\text{subsurface}}} \times \frac{\text{CO}_2 \text{ invasion}}{\text{CO}_2 \text{ evasion}}

modified from Sigman & Boyle Figure 5
How to Increase NU:

- export production rate
  - dust (iron)

- deep water exposure rate
  - salinity stratification
  - winds

DATA
Q: Where does atmospheric carbon go during glacial maxima?

2. Biologically pumped to the ocean interior?

- Low lat. nutrient reservoir: \( \downarrow \) atm. CO\(_2\) by 15-80 ppmv

- High latitude nutrient utilization: [additive] 25-40% higher nitrate util. \( \downarrow \) atm. CO\(_2\) by full 100 ppmv
Q: Where does atmospheric carbon go during glacial maxima?

1. Not enough
2. temp. Not enough
3. salinity
4. alkalinity likely role
5. biological pump favored hypothesis
SIGMAN & BOYLE HYPOTHESIS
d Ice Age Southern Ocean (hypothesis)

- Dust
- Salinity-stratified
- Subtropics
- STF
- Subantarctic
- PFZ
- Antarctic
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