During the glacial cycles, the atmospheric CO₂ varied between 180 and 280 ppm, a variation of 100 ppm, corresponding to 210 Pg C.

Where did it go?


The Earth’s Carbon Reservoirs

Fast Biosphere

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Amount</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>600 Pg</td>
<td>0.014</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>2100 Pg</td>
<td>0.051</td>
</tr>
<tr>
<td>Surface Ocean</td>
<td>700 Pg</td>
<td>0.017</td>
</tr>
<tr>
<td>Subtotal</td>
<td>3400 Pg</td>
<td>0.082</td>
</tr>
<tr>
<td>Deep Ocean</td>
<td>38000 Pg</td>
<td>0.918</td>
</tr>
<tr>
<td>Total</td>
<td>41400 Pg</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Where can 200 Pg C go during the glacial maximum?
Could be easily absorbed in the land: 2100 → 2300 Pg
or deep ocean: 38000 → 38200 Pg

Equilibrium Assumption:
Carbon Isotopes Since the Last Glacial Maximum

Richard McGehee, University of Minnesota

12/10/2013

Carbon Isotopes

The Earth’s Carbon Reservoirs


Then the land would have to absorb 11,000 Pg. Too much, even for peatlands.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Interglacial</th>
<th>Glacial Max</th>
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</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>800 Pg</td>
<td>400 Pg</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>2100 Pg</td>
<td>15200 Pg</td>
</tr>
<tr>
<td>Surface Ocean</td>
<td>700 Pg</td>
<td>430 Pg</td>
</tr>
<tr>
<td>Total</td>
<td>3400 Pg</td>
<td>16070 Pg</td>
</tr>
<tr>
<td>Deep Ocean</td>
<td>38000 Pg</td>
<td>25330 Pg</td>
</tr>
<tr>
<td>Total</td>
<td>41400 Pg</td>
<td>41400 Pg</td>
</tr>
</tbody>
</table>

Other factors such as ocean temperature and buffering reduce the effect, but not enough. See David Archer, The Global Carbon Cycle, Princeton Univ. Press 2010.

Terrestrial Carbon is 13C Depleted

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If terrestrial carbon sequestration and release is responsible for the variations in atmospheric carbon, then the atmosphere and ocean will be heavier in 13C during glacial maxima and lighter during interglacial periods.

Carbon Isotopes

Photosynthesis

$6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$

$\delta$ = 10°C

Fractionation is about 25%.

$\delta = \delta_0 - 0.025$

Fractionation also occurs for 14C.

Result: Plants, animals, coal, and oil are all lighter in 13C and 14C than inorganic carbon. Terrestrial carbon is light in 13C.

Carbon Isotopes

Late Pleistocene Glacial Cycles

Oogs!

Atmospheric CO2 and deep ocean 18O both increase during deglaciations. If the land were releasing the carbon, 13C would decrease.

Sharp decrease in 18O (rapid deglaciations)

Sharp increase in deep ocean 8°C

Sharp increase in atmospheric CO2

Carbon Isotopes

Paleocene-Eocene Thermal Maximum (PETM)

Seems to work better here. Sharp decrease in 18O, interpreted as a rapid increase in temperature. Sharp decrease in 8°C, interpreted as massive oxidation of sequestered organic carbon.
Carbon Isotopes Since the Last Glacial Maximum

Schmidt, et al, analyzed the ice core CO₂ samples for δ¹³C.
As the glaciers retreated, δ¹³C went down (17.5–15 kyr BP) then up (12–7 kyr BP).
What’s going on?

Note that peatlands continued sequestering carbon after the decrease in δ¹³C.
There must have been organic carbon released to balance the effect of peatland sequestration.
Homework: Quantify these effects.


Schmidt, et al
Peatlands sequestered carbon during shaded region (7–12 kyr BP),
consistent with the increase in δ¹³C.
Note the atmospheric CO₂ was roughly level, indicating an inorganic ocean source balancing the organic sequestration.

Gorham, et al


What about the earlier time?
“mystery interval”
- Deglaciation underway;
- Atmospheric CO₂ rising;
- Rapid decrease in δ¹³C.
Consistent with release of organic carbon stored in retreating glaciers.
Big problem: ¹⁴C
Carbon Isotopes Since the Last Glacial Maximum

Carbon Isotopes

Carbon 14 is created by cosmic rays in the upper atmosphere. Carbon 14 decays in the biosphere with a half-life of about 6000 years. Carbon 14 is the basis of carbon dating. Good for about 50,000 years. At 60,000 years, it is down to 2^{-10} of its original level. http://en.wikipedia.org/wiki/Carbon-14

Mystery Interval

A 15% drop in 14C corresponds to a release of 5000 Pg of old (at least 50,000 years old) carbon from somewhere into the atmosphere-ocean system.1

Did it come from the land? No, because 5000 Pg is a lot. Also, if it did, then it would have spiked the ocean acidity, and there is no trace of such an event in the record.

That leaves the deep ocean. The carbon in the deep ocean would have the right balance of dissolved carbon dioxide, carbonate, and bicarbonate and would not have affected the ocean acidity. However, it had to be out of circulation for at least 50,000 years.

Mystery: Where?


Homework

Explore the dynamics. Can you fit the data?

Math and Climate Seminar

Mathematics and Climate Research Network

Joint MCRN/IMA Math and Climate Seminar

Tuesdays 11:15 – 12:05
streaming video available at www.ima.umn.edu