Math and Climate Seminar IMA

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**Joint MCRN/IMA Math and Climate Seminar**

**Tuesdays 11:15 – 12:05**
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# Carbon Isotopes Since the Last Glacial Maximum

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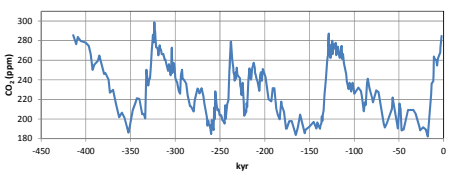
**Seminar on the Mathematics of Climate Change**
**School of Mathematics**
**December 10, 2013**

## Carbon Isotopes

**Atmospheric $CO_2$ (Vostok data)**




During the glacial cycles, the atmospheric $CO_2$ varied between 180 and 280 ppm, a variation of 100 ppm, corresponding to 210 Pg C.

***Where did it go?***

## Carbon Isotopes

**Units**

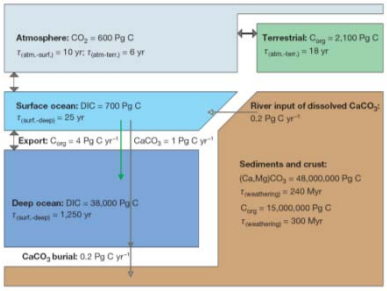
**tonne** = metric ton = 1000 kg = $10^6$ g
**Gt** = gigatonne = billion tonnes = $10^{15}$ g
**Pg** = petagram = $10^{15}$ g (= Gt)
atomic weight of carbon ≈ 12
molecular weight of carbon dioxide ≈ 44 (= 12+16+16)
Example: 240 Pg C ↔ 880 Pg $CO_2$

**Atmospheric Carbon**

**ppm** = parts per million (by volume or molecule)
1 ppm corresponds to about 2.1 Pg C
400 ppm : 840 Pg C ↔ 3080 Pg $CO_2$

## Carbon Isotopes

**The Earth's Carbon Reservoirs**




Sigman & Boyle, *Nature* **207** (2000), p.860

## Carbon Isotopes

**The Earth's Carbon Reservoirs**

| | Reservoir | Amount | | Proportion |
|---|---|---|---|---|
| Fast Biosphere | Atmosphere | 600 | Pg | 0.014 |
| | Terrestrial | 2100 | Pg | 0.051 |
| | Surface Ocean | 700 | Pg | 0.017 |
| | Subtotal | 3400 | Pg | 0.082 |
| | Deep Ocean | 38000 | Pg | 0.918 |
| | Total | 41400 | Pg | 1.000 |

***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:
Atmosphere : Surface Ocean : Deep Ocean = 6:7:380

## Carbon Isotopes

**The Earth's Carbon Reservoirs**

Assumption: Atmosphere : Surface Ocean : Deep Ocean = 6:7:380
Then the land would have to absorb 13,000 Pg.
Too much, even for peatlands.

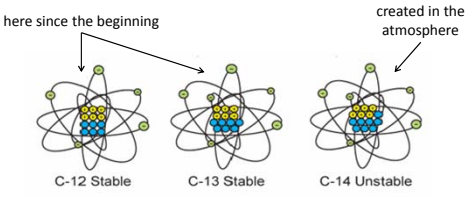
| Reservoir | Interglacial | Glacial Max |
|---|---|---|
| Atmosphere | 600 Pg | 400 Pg |
| Terrestrial | 2100 Pg | **15200 Pg** |
| Surface Ocean | 700 Pg | 470 Pg |
| Subtotal | 3400 Pg | 16070 Pg |
| Deep Ocean | 38000 Pg | 25330 Pg |
| Total | 41400 Pg | 41400 Pg |

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.

***Then there's $^{13}C$.***

## Carbon Isotopes

Three Flavors of Carbon




99% 1% trace

## Carbon Isotopes

**Photosynthesis**

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

$\delta_1 = \delta^{13}C$ $\delta_2 = \delta^{13}C$

Fractionation is about -25‰.

$$\delta_2 \approx \delta_1 - 0.025$$

Fractionation also occurs for $^{14}C$.

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

## Carbon Isotopes

**Terrestrial Carbon is $^{13}C$ Depleted**

| Reservoir | Interglacial | Glacial Max | |
|---|---|---|---|
| Atmosphere | 600 Pg | 400 Pg | |
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| Total | 41400 Pg | 41400 Pg | |

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

## Carbon Isotopes

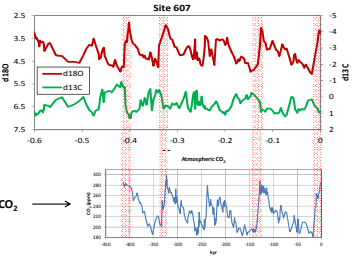
**Late Pleistocene Glacial Cycles**
**Oops!**

Atmospheric $CO_2$ and deep ocean $^{13}C$ both **increase** during deglaciations.
If the land were releasing the carbon, $^{13}C$ would decrease.

Sharp decrease in $\delta^{18}O$ (rapid deglaciations)

Sharp increase in deep ocean $\delta^{13}C$

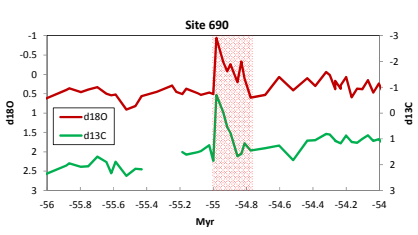
Sharp increase in atmospheric $CO_2$




## Carbon Isotopes

**Paleocene-Eocene Thermal Maximum (PETM)**

Seems to work better here.
Sharp decrease in $\delta^{18}O$, interpreted as a rapid increase in temperature.
Sharp decrease in $\delta^{13}C$, interpreted as massive oxidation of sequestered organic carbon.



## Carbon Isotopes

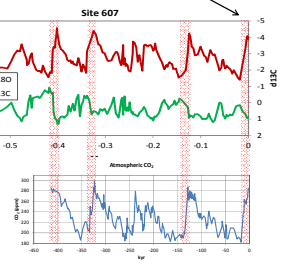
**Late Pleistocene Glacial Cycles**

What about the latest deglaciation?

Sharp decrease in $\delta^{18}O$ (rapid deglaciations)

Sharp increase in deep ocean $\delta^{13}C$

Sharp increase in atmospheric $CO_2$



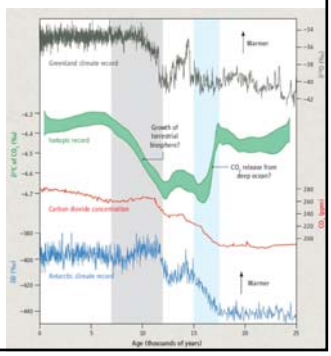

## Carbon Isotopes

**Last 25,000 years**

Schmidt, et al, analyzed the ice core $CO_2$ samples for $^{13}C$.

As the glaciers retreated, $^{13}C$ went **down** (17.5 – 15 kyr BP, then **up** (12 – 7 kyr BP).

What's going on?



Edward Brook, "The Ice Age Carbon Puzzle," *Science* **336**, 682 (2012)

## Carbon Isotopes

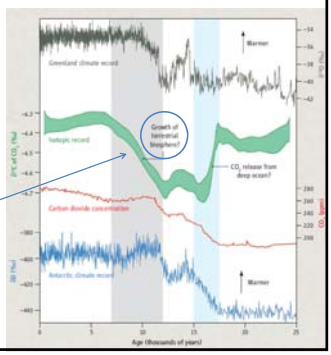
**Last 25,000 years**

Schmidt, et al, analyzed the ice core $CO_2$ samples for $^{13}C$.

As the glaciers retreated, 13C went down (17.5 – 15 kyr BP, then up (12 – 7 kyr BP).

What's going on?

Let's look at this region.



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## Carbon Isotopes

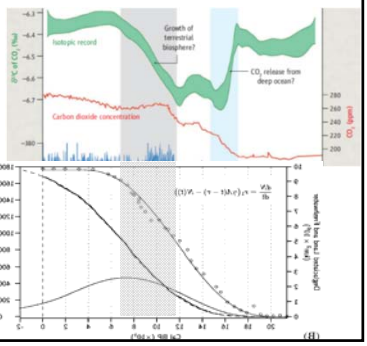
**Last 25,000 years**

Schmidt, et al

Peatlands sequestered carbon during shaded region (7-12 kyr BP), consistent with the increase in $^{13}C$.

Note the atmospheric $CO_2$ was roughly level, indicating and inorganic ocean source balancing the organic sequestration.

Gorham, et al



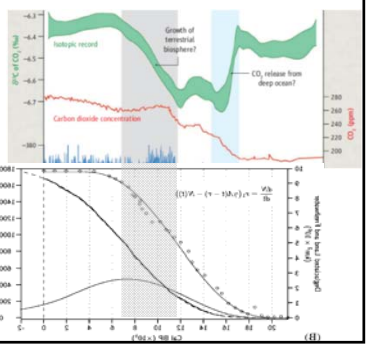
## Carbon Isotopes

**Last 25,000 years**

Note that peatlands continued sequestering carbon after $^{13}C$ leveled off.

There must have been organic carbon released to balance the effect of peatland sequestration.

Homework: Quantify these effects.



## Carbon Isotopes

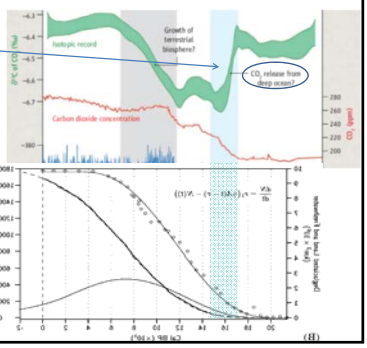
**Last 25,000 years**

**What about the earlier time? "mystery interval"**

- Deglaciation underway.
- Atmospheric $CO_2$ rising.
- Rapid decrease in $^{13}C$.

Consistent with release of organic carbon stored in retreating glaciers.

**Big problem: $^{14}C$**

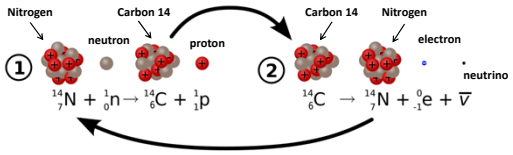


## Carbon Isotopes

### Carbon 14

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.



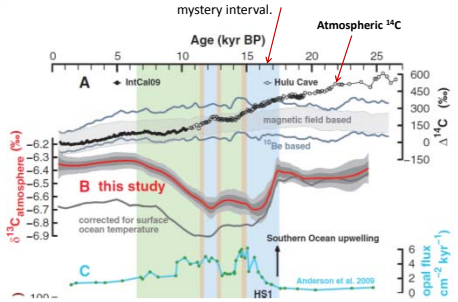

Carbon 14 is the basis of carbon dating. Good for about 50,000 years. At 60,000 years, it is down to $2^{-10}$ of its original level.

http://en.wikipedia.org/wiki/Carbon-14

## Carbon Isotopes

### Mystery Interval

Atmospheric $^{14}C$ decreased by a whopping 15% during the mystery interval.




Schmidt, el al. "Carbon Isotope Constraints on the Deglacial $CO_2$ Rise from Ice Cores." *Science* **336** (2012)

## Carbon Isotopes

### Mystery Interval

A 15% drop in $^{14}C$ 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.

***But it had to be out of circulation for at least 50,000 years.***

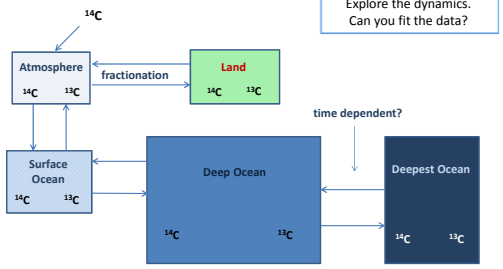
***Mystery: Where?***

1. Wally Broecker and Elizabeth Clark, "Search for a glacial-age $^{14}C$-depleted ocean reservoir," *Geophysical Research Letters* **37** (2010)

## Carbon Isotopes

### Mystery Interval

***Homework***
Explore the dynamics.
Can you fit the data?

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