Ice age deep ocean circulation and atmospheric CO₂

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Atmospheric CO₂ (EPICA Dome C)

- scales closely with Antarctic temperature (and global ice volume)
- *challenge*: why do these records look so similar?
- implies a *common forcing*
Earth’s pre-industrial carbon reservoirs

Glacial atmospheric lowering requires storage in another reservoir
(“Everybody’s gotta be somewhere” – Dean Martin)

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>600 PgC</td>
</tr>
<tr>
<td>Surface ocean</td>
<td>1000</td>
</tr>
<tr>
<td>Deep ocean</td>
<td>38,000</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>2200</td>
</tr>
<tr>
<td>Seds+crust</td>
<td>80,000,000</td>
</tr>
</tbody>
</table>

smaller during LGM (source)

- major glacial sink
- positive feedback (kyr)
- too slow (Myr)

\[ pCO_2 = \frac{[CO_2(aq)]}{K_0} \]
Dissolved inorganic carbon stable isotopes ($\delta^{13}C$)

- biological pump depletes surface DIC, enriches deep sea
- since algae preferentially use $^{12}$CO$_2$, $\delta^{13}C$ follows an inverse pattern
- *air-sea exchange* also enriches DIC $\delta^{13}C$
- DIC max ($\delta^{13}C$ min) is found in modern deep North Pacific (dead end)
- deep upwelling in the Southern Ocean and productivity is limited: CO$_2$ leak

Kroopnick (1985) DSR
Benthic foraminiferal $\delta^{13}C$ in the Atlantic

- **modern**: high-$\delta^{13}C$ (low-DIC) NADW dominates
- **LGM**: high-$\delta^{13}C$ GNAIW overlying very low-$\delta^{13}C$ AABW
- Southern Ocean was most depleted water mass in LGM ocean
- implies LGM deep Southern Ocean accumulated carbon via remineralized organic matter, and/or had poor contact with the atmosphere

*Curry and Oppo (2005) *Paleoceanography*
Air-sea component of $\delta^{13}$C from comparison to Cd

- dissolved Cd behaves like the nutrient phosphate
- should vary inversely with $\delta^{13}$C except for air-sea exchange
- LGM Atlantic benthic Cd/Ca is broadly similar to $\delta^{13}$C

Marchitto and Broecker (2006)
Marchitto and Broecker (2006) *G-Cubed*

- LGM AABW: lower $\delta^{13}C$ than expected from Cd: low $\delta^{13}C_{as}$
- modern AABW: high $\delta^{13}C_{as}$
- suggests poorer air-sea contact during LGM

- what can we learn from $^{14}C$?

Charles et al. (1993) *Paleoceanography*
Reconstructing past $\Delta^{14}C$ distributions

- $^{14}C$ beta decays with half life of 5730 yr (Godwin, 1962)
- decay equation: $(^{14}C/^{12}C)_{\text{meas}} = (^{14}C/^{12}C)_0 e^{-\lambda t}$

- **dating:** solve for $t$ using an assumed value for $(^{14}C/^{12}C)_0$

- **tracer:** if $t$ is known independently, can solve for $(^{14}C/^{12}C)_0$
- can use this method to reconstruct paleo-$\Delta^{14}C$ of the atmosphere or ocean
Atmospheric $\Delta^{14}C$ reconstruction

- glacial $\Delta^{14}C$ was higher than predicted from a weaker geomagnetic field
- necessitates a “smaller” carbon cycle (less ocean uptake)
- requires $\Delta^{14}C$ depletion in the deep ocean (elusive)

More $^{14}C$ in atmosphere
Weaker geomagnetic field
Less ocean uptake

Hughen et al. (2006) QSR
Intermediate-depth (Baja Calif.) $\Delta^{14}C$ reconstruction
- like other low-latitude records, reflectance displays clear “Greenland pattern”
- established through 21 tie points to GISP2 $\delta^{18}O$ record
- aided by a high and very constant sedimentation rate (30 cm/kyr)

Marchitto et al. (2007) Science
Results: Baja California intermediate water $\Delta^{14}C$
- extremely $^{14}C$-depleted waters during deglaciation
- up to 4 kyr old if projected back to atmosphere along decay curve
- similar to age of presumed deep, old reservoir

Marchitto et al. (2007) *Science*
Δ14C signal of ocean’s CO2 release

• very old intermediate waters during two CO2 increases
• partial relaxation during Antarctic Cold Reversal
• coincides with main parts of the atmospheric Δ14C drop
Link with Southern Ocean deep convection

- **LGM**: expanded sea ice, poor ventilation, CO$_2$ ‘leak’ capped
- **deglaciation**: sea ice retreat, deep convection/upwelling
- simultaneous warming and release of old CO$_2$
- temporarily interrupted by Antarctic Cold Reversal

Keeling (2007) *Science* Perspective
Link with North Atlantic deep convection

- NADW ‘shutdown’ inferred from $^{231}\text{Pa}/^{230}\text{Th}$ during Heinrich event 1; reduction during Younger Dryas
- old CO$_2$ releases closely correspond to NADW reductions

- overturning in Southern Ocean as response to reduced NADW?
- bipolar seesaw warming, sea ice retreat, westerly contraction?
- deep water formation required to balance global deep upwelling?

Pa/Th from McManus et al. (2004) *Nature*
Two take-home points

• $^{13}\text{C}$ and Cd/Ca suggest the ice age deep ocean was more poorly ventilated, especially around Antarctica

• $^{14}\text{C}$ depletion of intermediate waters during deglaciation appears to track the release of ‘old’ carbon sequestered in the deep sea, possibly triggered from the North Atlantic

Challenges

• map the deglacial $^{14}\text{C}$ events using other intermediate depth cores: Arabian Sea, southern Chile

• find the old, deep glacial reservoir

• better incorporate biogeochemical tracers into numerical models