What can we learn from the paleo record about past changes in ocean productivity and controls of atmospheric CO$_2$?

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Exploring Ocean Iron Fertilization, WHOI, September, 2007
Ice core records show tight coupling between CO₂ & Climate

From Brook, 2005
Comment on Siegenthaler et al., 2005
How did the ocean lower glacial atmospheric CO$_2$ levels?

Plausible mechanisms

1) **Increased strength of the biological pump**
   - Increase nutrient inventory (capacity)
   - Increase nutrient utilization (efficiency; today at ~50%)

2) **Increase ocean ALK/DIC ratio ([CO$_3^{2-}$])**
   - Continental weathering
   - Shelf-basin fractionation (“Coral Reef” hypothesis)
   - C-org/CaCO$_3$ ratios (“Rain Ratio” hypothesis)
What does “efficiency” of the biological pump mean?

It is the fraction of upwelled nutrients that are utilized and exported to depth as organic matter.

Preformed nutrients are the master variable to characterize the efficiency of the biological pump.
Sensitivity of CO$_2$ to preformed nutrients

Princeton Ocean GCM runs with different nutrient utilization scenarios.
Constant ocean nutrient inventory

Marinov et al., Nature, 2006
Only about half of the upwelled nitrate is used by phytoplankton. Efficiency of the Biological Pump today is low. Potential to alter CO$_2$ is high.

From: iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94
Martin’s “Iron Hypothesis”
Dust is inversely correlated with CO$_2$ in Antarctic ice core records -- is there a causal relationship?

Martin (1990) reasoned that increased dust fluxes relaxed Fe limitation in the glacial Southern Ocean, allowing increased efficiency of the biological pump to draw down atmospheric CO$_2$.
Antarctic Ice Core
Dust (Fe) - CO$_2$ (anti)correlation

Fe flux from Wolff et al., Nature 2006; CO$_2$ from Brook, Science 2005
Questions to ask of the paleo record:

1) Did dust affect Productivity in HNLC regions?

2) Did other sources of Fe have a significant impact on productivity?

3) What caused glacial CO$_2$ to be 80-100 ppm lower?
Questions to ask of the paleo record:

1) Did dust affect Productivity in HNLC regions? (No)

2) Did other sources of Fe have a significant impact on productivity? (I think so)

3) What caused glacial CO$_2$ to be 80-100 ppm lower?
Search for evidence of dust influence in regions with paired records of dust flux and paleoproductivity.
Equatorial Pacific Dust-Climate Correlation

- Dust flux proxy is tightly correlated with climate
- Glacial-interglacial amplitude ~2.5X at all sites
Equatorial Pacific - Antarctica Correlation

Internally-consistent change in dust flux from at least 3 sources suggests control by global hydrological cycle

Winckler et al., submitted
Proxy records for paleoproductivity and dust flux are uncorrelated over the last 3 glacial cycles.
Productivity shows no response to a 2-fold drop in dust flux over the last deglaciation.
Equatorial Pacific:

Increased glacial dust fluxes had no detectable effect on export production.
What about the Southern Ocean?

Here, increased nutrient utilization south of the Antarctic Polar Front has the greatest potential to affect atmospheric CO₂.
High glacial productivity is restricted to the Subantarctic zone.
Iron fertilization was not pervasive throughout the Southern Ocean.

Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005
Sites around the Southern Ocean with detailed records showing glacial productivity < interglacial productivity.

Nutrient utilization south of the APF has the greatest potential to impact global inventory of preformed nutrients. Marinov et al., (2006)
SW Pacific - Two Cores & Three Proxies
Consistently show glacial productivity < Holocene

Anderson et al., 2002
S Atlantic Productivity anti-correlated with dust

S Atlantic core RC13-259 - 54°S, 5°W

Diatom Productivity Proxy
Opal Flux (g cm⁻² ky⁻¹)

Export Production Proxy
xsBa Flux (mg cm⁻² ky⁻¹)

EDC Fe Flux (µg m⁻² y⁻¹)

Age (ka)

Opal & Ba fluxes: Anderson et al., 2002 - EPICA Dome C Fe flux: Wolff et al., 2006
Site is downwind of the Patagonian dust source

If dust-borne Fe stimulated nutrient utilization in the glacial Southern Ocean, then it should have been evident here.
Southern Ocean (South of APF):

Any iron fertilization by increased glacial dust fluxes was more than offset by other factors that reduced export production.
Did Fe have any impact on glacial productivity in the Southern Ocean?
LGM minus Modern Export Production
(synthesis of published data; all proxies)

“Hot Spots” - Subantarctic Sites Experienced High Productivity

Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005
Examples from Subantarctic “Hot Spot”
Higher Subantarctic Productivity in LGM supported by order of magnitude greater C-org burial

Patterns reproduced in two cores

Changes were BIG!

Anderson et al., 1998, 2002
Why such different behavior among cores downwind of Patagonia?

Blue = Lower glacial productivity; Red = Higher glacial productivity
Contours = Summer Nitrate µM; ample nutrients N of APF
Why such different behavior among cores?

Is the APF (convergence) a barrier to supply of essential factor?
Patagonian ice sheet during glacial times delivered Ice-Rafted Debris (IRD) to the Southern Ocean
Modern ALACE float tracks show that currents would have carried Patagonian IRD into the S Atlantic.

Courtesy of S. Gille, SIO
Icebergs as a source of Fe - location matters!

Antarctic ➔ Subpolar

Alaskan photos from John Crusius

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
APF would have been a barrier to icebergs, IRD, and any Fe released from IRD
Evidence for Patagonian Fe fertilization?

1) YES - Isotopic and mineralogical data; Diekmann, Walter, Kuhn, & others at AWI;
2) Nd isotopes in Cape Basin (highlighted star)
Cape Basin: Nd isotopes correlate with productivity proxies… May reflect Fe supply.

Alkenone Flux
Sachs & Anderson, 2003

Uranium
Sachs & Anderson, 2005

εNd
Piotrowski et al., 2005
Hypothesis- “Hot Spots” reflect Fe from Patagonia & Kerguelan
Current work on S Pacific shows no hot spots; supports local Fe fertilization
Kohfeld, LeQuéré, Harrison and Anderson, Science, 2005
Summary:

No evidence for Fe fertilization of HNLC regions (EqPac & So. Ocean) by increased glacial dust fluxes.

Subantarctic: Hot spots of high productivity may have been fertilized by local sources of Fe; not dust, maybe icebergs.

Impact of Subantarctic on CO$_2$ minor because disconnected from main inventory of preformed nutrients.

Increased ocean stratification, with feedbacks from CaCO$_3$ compensation, lowered glacial atm. CO$_2$

(Marchitto et al., Science, 2007)
What caused lower glacial CO$_2$?
Increased ocean stratification was a primary factor.

Indirect evidence from $^{14}$C of benthic forams at 700m in N Pacific. Accelerated overturning of deep waters brought CO$_2$ to the atm., and $^{14}$C-depleted DIC, both to intermediate depths and to the atm.

Marchitto et al, Science, 2007
More direct evidence: Deglacial increase in So Ocean upwelling coincided with rise in CO₂ and drop in $\Delta^{14}C$ of Atm. CO₂.

Increased Upwelling

Opal flux from TN057-13PC  53.2°S, 5.1°E

- F(opal)
- Hughen06
- IntCal04

$\Delta^{14}C$ of Atm. CO₂ (%o)

- CO₂ from Monnin et al., EPSL, 2004

IntCal Atm. $^{14}C$ from Reimer et al., 2004

Hughen Atm. $^{14}C$ from Cariaco Basin. Hughen et al., 2006
Deglacial increase in upwelling is evident at sites all around the Southern Ocean

Red star = TN057-13