Reorganization of global winds with Abrupt Climate Change and its impact on CO₂

Bob Anderson

With contributions from
Shahla Ali, Louisa Bradtmiller
Simon Nielsen, Martin Fleisher
Brent Anderson and Lloyd Burckle

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Ice core records show tight coupling between CO$_2$ and climate

From Brook, 2008
Wind-driven upwelling south of the Zero in Wind Stress Curl “ventilates” deep waters

Upwelling ventilates CO$_2$-rich deep water masses S of the APF

Figure of K Speer redrawn by T Trull
Ventilation and CO$_2$ exchange controlled by position of the SH Westerlies?

Northward shift of winds reduced ventilation during glacials. Evidence for wind shift from precipitation proxy records.

Toggweiler, 2006
Evidence for increased upwelling during deglaciations?

GOAL:
Demonstrate that opal flux in So. Ocean sediments is a proxy for upwelling, and that it is correlated with the deglacial rise in CO$_2$. 
Principle: Upwelling brings nutrients (N, P, Si) to the surface as well as CO$_2$.

Maximum nutrient supply is between the APF and the SACCF.

Figure of K Speer redrawn by T Trull
Principle: Between APF and SACCF Si is consumed by diatoms almost completely

Although N and P go largely unused, nearly all Si is consumed

Figure from US JGOFS/AESOPS
Principle: Between APF and SACCF Si is consumed by diatoms almost completely.

Although N and P go largely unused, nearly all Si is consumed. This is true throughout the Southern Ocean.

Figure from Sarmiento et al., 2004
Review: Features of the region between the APF and SACCF

- Maximum upwelling and nutrient supply
- Nearly all Si used by diatoms
- Annual opal production is limited by Si, i.e., by upwelling
Implication for the region between the APF and SACCF

Production of opal by diatoms in this region can exceed today’s maximum values only by increasing the supply of dissolved Si...

...i.e. By increasing the rate of upwelling
Sites where deglacial maxima in opal burial have been observed

Feature occurs:

- South of the APF
- In all sectors
- Results from selected sites
Deglacial maxima in opal burial in 3 sectors of the Southern Ocean

Opal burial flux:

- Peaks during deglaciation
- Correlates with $^{231}\text{Pa}/^{230}\text{Th}$
- Flux reflects diatom production, not opal preservation
Maximum So. Ocean upwelling coincided with deglacial rise in CO$_2$

SUMMARY OF EVIDENCE:

Peak upwelling (opal flux) coincided with:
- warming in Antarctica,
- deglacial rise in CO$_2$
- deglacial drop in atm. $\Delta^{14}$C

Including pause during ACR
Atm CO$_2$ increased during NH cold intervals surrounding earlier HEs

High resolution CO$_2$ record from Byrd ice core (red CO$_2$) extended through last glacial period (Ahn and Brook, 2008)
TN057-14: Opal flux upwelling proxy through last glacial period

Sediment focusing changed with climate.

TN057-13 has an expanded deglacial section.

TN057-14 has an expanded section during the last glacial period.
Upwelling proxy correlates with pCO$_2$ throughout last glacial period

TN057-14: Increased upwelling (opal flux) coincided with:

- Cold in Greenland
- Warmth in Antarctica
- Rising CO$_2$
- pCO$_2$ (ppm)

Increased upwelling
Deglacial Si supply to surface waters south of the APF exceeded supply before or after; increased upwelling is the only plausible cause. Upwelling correlated with rising atmospheric CO$_2$. Coincided with HS1 and the YD.

Increased upwelling (opal burial) coincided with earlier periods of rising atmospheric CO$_2$.

Wind-driven upwelling in the Southern Ocean is a primary mechanism driving changes in atmospheric CO$_2$. 
Proposed Trigger

Heinrich Stadials (and Younger Dryas)

• Extreme cold in N. Hemisphere
• N. Hemisphere iceberg discharge
• Increased sea ice covered N. Atlantic
• Reorganization of wind systems
Teleconnection via winds
(global atmospheric circulation)

• **Change in N. Hemisphere Westerlies** during HE1 and YD recorded in Lake Lahontan level (Benson, 1995) and during YD recorded in German Lake sediments (Brauer et al., 2008)

• **Southward shift of ITCZ** and reorganization of monsoons during HEs (many references)

• **Southward shift of S. Hemisphere westerlies:**
  Shift in S Atlantic STF (Barker et al., 2009)
  Increased Precip in New Zealand (Whittaker, 2008)
  SST records off S. Chile (Lamy et al., 2007)
  Coupled GCMs (Timmermann et al., 2007)
Rapid shift in S Atlantic STF

Rapid drops in polar foram species at 41°S (Atlantic) during HS1 and HS2 attributed to wind forcing and southward shift in the Subtropical Front.

(Barker et al., 2009)
Increased precip over South Island of New Zealand during HEs

Reduction of $\delta^{18}$O in speleothem CaCO$_3$ attributed to increased precipitation during Heinrich Events.

(Whittaker, 2008)
Increased precip over S. Island of New Zealand linked to intensity of westerlies

(Whittaker, 2008)
Wind stress at 60°S increases in response to waterhosing (~HEs)
Increased wind stress at 60°S drives upwelling in the So. Ocean

Maximum wind stress at the latitude of the Drake Passage favors upwelling of deep CO₂-rich water masses.

Toggweiler, 2006
Abrupt Changes in Winds and CO$_2$

Extreme N Hemisphere cold events (HEs) induced reorganization of global atmospheric circulation.

Southward shift of SH Westerlies during HEs forced increased upwelling in the Southern Ocean and release of CO$_2$ from deep waters.

Asymmetry of polar temperature changes caused the southward shift of SH Westerlies to be more extreme during HEs than during the Holocene or warm interstadials.
Are these relationships limited to “glacial” conditions?

TN057-14: Increased upwelling (opal flux) coincided with:

- Cold in Greenland
- Warmth in Antarctica
- Rising CO$_2$

$pCO_2$ (ppm)

Increased upwelling
Earliest abrupt change of last climate cycle: Greenland Stadial 26 @ ~ 118 ka

GS 26:
ODP 980 (N Atlantic) record shows cooling SST and detectable increase in IRD.

Oppo et al., 2006

Note different age models.

SST = solid
IRD = dashed
Earliest abrupt change of last climate cycle: GS 26 has widespread footprint

Atlantic SST:
- Subpolar
- Subtropical

Speleothems:
- China
- Israel

Austrian alps speleothem

NGRIP

According to Meyer et al., 2008, although age models differ slightly, many records show abrupt changes at ~118ka consistent with cooling in the N Atlantic.
Earliest abrupt change of last climate cycle: GS 26 has widespread footprint

N Atlantic Polar foraminifera

NGRIP

Italian Speleothems

Iberian margin

Planktic forams

W Med.

Planktic forams

Brazilian speleothem

Drysdale et al., 2007
Earliest abrupt change of last climate cycle: GS 26 has features of Heinrich Stadials

NGRIP and Vostok aligned by gases:
- Cooling in Greenland
- Warming in Antarctica
- Rising CO₂

Landais et al., 2006
Earliest abrupt change of last climate cycle: GS 26 has widespread footprint

Although age models differ slightly, many records show abrupt changes at ~118ka consistent with cooling in the N Atlantic.

Atlantic SST:
- Subpolar
- Subtropical

Speleothems:
- China
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Austrian alps speleothem

NGRIP

Meyer et al., 2008
Earliest abrupt change of last climate cycle: GS 26 has widespread footprint

Austrian Alps speleothem:
- Abrupt drop in $\delta^{18}$O at 118ka attributed to increased seasonality.
- Colder winters.
- Consistent N Atlantic sea ice effect of Denton et al., 2005.

Meyer et al., 2008
Conclusions: Abrupt NH Coolings…

Triggered by (freshwater-induced) expansion of N Atlantic sea ice.

Transmitted globally by winds.

Raise atm CO$_2$ by upwelling in So. Ocean.

Terminations are a special case.

Sequence may have occurred as early as 118 ka. Terminating last interglacial. With small NH ice sheets.
Test systematic pattern of N Atlantic sea ice trigger and global wind teleconnection during Abrupt Change events.

Discriminate between consequences of winds versus AMOC.

Investigate other factors affecting global winds and their impact on CO$_2$ and climate.