Ice cores, air bubbles, and climate change

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Climate Literacy Network

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What causes ice age cycles?

**TAKE-HOME MESSAGES:**

1. Wobble and tilt of Earth’s spin axis
2. Amplified by CO2 variations
3. Meltdowns aided by abrupt shutdown of Atlantic ocean circulation
Milankovitch theory

High-latitude northern summer sunshine intensity influences growth/decay of Northern Hemisphere ice sheets and thus global climate.
Earth’s orbit: pacemaker of the ice ages
Polar ice cores:

- Dated by counting annual layers
- Preserve past atmospheres in air bubbles in the ice!
Trapped gases reveal a cornucopia of information about past climate and its feedbacks:

Climate forcing via greenhouse effect: CO2, CH4, N2O
Astronomical dating of ice cores: O2/N2
Mean ocean temperature: Kr/N2, Xe/N2
Rapid temperature change at ice sheet surface: 15N/14N of N2
        40Ar/36Ar, 86Kr/82Kr
Asian and African monsoon strength: 18O/16O of O2
Fossil vs. biological sources of methane: 14C/12C of CH4
(list goes on....)
Ice cores give us past CO2 concentrations
CO₂, CH₄ and estimated global temperature (Antarctic ΔT/2 in ice core era)

Termination I temperatures, Dome Fuji and Dome C CO₂
Paradox #1:

Why does Antarctic temperature remain in a stable, cold state despite several thousand years (22-18 ka) of orbital forcing?

And why does it begin to warm rather abruptly at 18 ka?
Atmosphere is well-mixed, so long-lived gases are the same everywhere
(same core, so no relative dating problem!)

ADVANTAGE: integrates all sources
DISADVANTAGE: no information about location of sources

Methane responds rapidly due to short lifetime (8 yr)
O2 lifetime ~1000 yr
Kr, Xe ~constant in ocean-atmosphere system
Oxygen-18/16 ratio of atmospheric O2 = \textit{d}18\textit{O}_{atm}

d_{18}O = \frac{[^{18}O/^{16}O_{sample}]}{[^{18}O/^{16}O_{standard}]} - 1 \times 10^3\%

Standard is contemporary La Jolla air

METHOD

Measure isotopes of O2 in air from ice core bubbles, following procedure of Sowers et al. (1989) with modification to remove CO2 cryogenically. Correct for gravitational/thermal fractionation in firn layer:

\textit{d}18\textit{O}_{atm} = \textit{d}18\textit{O}_{measured} - 2 \cdot \textit{d}15\textit{N}_{measured}
Last 40 kyr air $\delta^{18}$O and inferred fractionation ($\Delta\varepsilon_{\text{LAND}}$)

- Chinese stalagmite $^{18}$O, %o PDB
- air O-18 data
- change in Dole Effect
- land fractionation
- Hulu Cave O-18
- Dongge cave O-18

Age, kyr BP

TIME

$^{18}$O, or difference in $^{18}$O from present value
How does a melting ice sheet suppress the Asian monsoon?
Cheng et al. (2009) hypothesis
Gas solubility is a function of temperature

- Xenon
- Krypton
- N₂
A method to measure \( \text{Kr/N}_2 \) ratios in air bubbles trapped in ice cores and its application in reconstructing past mean ocean temperature

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[1] We describe a new method for precise measurement of \( \text{Kr/N}_2 \) ratios in air bubbles trapped in ice cores and the first reconstruction of atmospheric \( \text{Kr/N}_2 \) during the last glacial maximum (LGM) \( \sim 20,000 \) years ago. After gravitational correction, the \( \text{Kr/N}_2 \) record in ice cores should represent the atmospheric ratio, which in turn should reflect past ocean temperature change due to the dependence of gas solubility on temperature.
\[\text{CO}_2, \text{CH}_4\] and estimated global temperature (Antarctic \(\Delta T/2\) in ice core era)

GISP2 and Dome Fuji δKr/N₂, δXe/N₂, Dome Fuji and Dome C

Headly et al., in prep.

Ahn and Brook

Monnin et al., Kawamura et al.

ΔT, °C

0

2

4

GISP2 Kr

GISP2 Xe

d86Kr/4

d15N

d18Oice

Dome Fuji Kr

Dome Fuji Xe

CO₂

δ¹⁵N

35,000

30,000

25,000

20,000

15,000

10,000

5,000

0

TIME------->

age (yr BP)

Kr

Xe

CO₂

-2

-1

0

1

2

3

4
CO2 Termination I timing

Ahn et al., 2007
Why would the deep ocean warm 2°C when the bipolar see-saw was in its warm-south mode?

- volume of the deep ocean is dominated by Antarctic waters
- less deep water formation by sea-ice brine rejection
  with more open-ocean convection?

Reduction in Antarctic sea ice would also increase atmospheric CO2
Wind-Driven Upwelling in the Southern Ocean and the Deglacial Rise in Atmospheric CO₂


Wind-driven upwelling in the ocean around Antarctica helps regulate the exchange of carbon dioxide (CO₂) between the deep sea and the atmosphere, as well as the supply of dissolved silicon to the euphotic zone of the Southern Ocean. Diatom productivity south of the Antarctic Polar Front and the subsequent burial of biogenic opal in underlying sediments are limited by this silicon supply. We show that opal burial rates, and thus upwelling, were enhanced during the termination of the last ice age in each sector of the Southern Ocean. In the record with the greatest temporal resolution, we find evidence for two intervals of enhanced upwelling concurrent with the two intervals of rising atmospheric CO₂ during deglaciation. These results directly link increased ventilation of deep water to the deglacial rise in atmospheric CO₂.

Scientists have long sought to unravel the combination of physical and biogeochemical processes responsible for the tight coupling between atmospheric CO₂ concentrations and Earth’s climate that has persisted for at least the last 600,000 years (1), with the expectation that knowledge of the processes linking CO₂ and climate in the past will improve projections of future climate change under rising anthropogenic CO₂ levels. It is believed that no single mechanism can account for the full amplitude of past CO₂ variability (2, 3). Although multiple processes operating synergistically may be involved (4–8), there is general agreement that lower CO₂ levels are associated with upwelling and atmospheric CO₂ during deglaciation (4, 15, 16); and the precipitous drop during deglaciation in 14C activity of dissolved inorganic carbon (DIC) in North Pacific intermediate waters, requiring injection of carbon from a reservoir long isolated from the atmosphere, such as the deep sea (17). However, until now there has been no direct evidence for a change in Southern Ocean circulation that could have altered substantially the partitioning of CO₂ between the atmosphere and the deep sea.

Biogenic opal as an upwelling proxy. Burial of biogenic opal, the microscopic tests of marine diatoms, provides a link to past changes in upwelling and ventilation of deep-water masses in the Southern Ocean. Diatoms live in the euphotic zone where they use dissolved silicic acid (H₄SiO₄) to form opal tests. The zone of maximum production of biogenic silica (opal) occurs just south of the Antarctic Polar Front (APF) (18, 19), corresponding to the region of maximum supply of dissolved nutrients (including Si) to surface waters by upwelling of nutrient-rich deep-water masses (Fig. 1) (20).

Within the zone of maximum opal production, diatom growth throughout spring and summer typically depletes surface waters of dissolved Si supplied during the previous winter (20, 21). Consequently, although the physiological status and growth rate of individual diatom cells may be limited by iron (22), the total amount of biogenic opal produced each year within this region is ultimately limited by the supply of dissolved Si (18–20). Therefore, past changes in the production and burial of opal within this region are tied directly, although not necessarily linearly, to the rate of upwelling.

Deglacial changes in upwelling. Three sediment cores (TN057-13PC, NBP9802-6PC, and E27-23PC; Fig. 2) with relatively high accumulation rates [10 to 20 cm/kyr (10⁴ years)]
Conclusions

Oxygen-18 of O2 confirms widespread low-latitude rainfall shifts during abrupt climate change

Oxygen-18 of O2 and methane have interesting differences - southern hemisphere sources of methane?

Kr and Xe suggest ~2 deg of mean ocean temperature warming between 18-15 ka, synchronous with CO2 rise.  
[We still need to refine the gravitational correction, though.]

Glacial inception also shows synchronous CO2, Kr, Xe.

Consistent with existing models of atmospheric CO2 control by deep stratification (Toggweiler, 1999) or Antarctic sea ice (Stephens and Keeling, 2000).

CO2, methane, southern tropical rain all start rising at 18 ka, when mean ocean warms 2°C and Antarctica warms!

Does the bipolar seesaw play a key role in Terminations?
Wetlands: the dominant natural source of methane to the atmosphere

- Methanogenic bacteria produce methane in anaerobic conditions in wetlands -- the leading natural source of methane in the atmosphere today
- The end-of-Younger-Dryas event made climate both warmer and wetter
- Wetlands respond to warmer and wetter conditions with increased methane production
- A warmer, wetter climate should also increase the extent of wetlands
Modeled natural wetland methane emissions

Kaplan, 2002 GRL
The Hydrate Hypothesis

- Methane hydrate is an ice-like compound composed of water and methane
- Widely distributed on continental shelves in the oceans and in permafrost
- Stable at low temperatures and high pressures
- As the oceans warmed at the end of the Younger Dryas event, large quantities of methane hydrate may have destabilized; some of the released methane may have made it into the atmosphere
Pakitsoq, West Greenland: The hunt for ancient methane C-14 samples
Clathrate hypothesis

Wetland hypothesis

Petrenko et al., 2009
Science