LGM Temperatures

**Rationale:** What did the Earth’s climate system look like when pCO2 was 200ppm?

- Sea Surface Temperature
  - Faunal
  - Oxygen isotopes
  - Mg/Ca
  - Alkenone
- Land surface temperature
  - Ice cores
  - Noble gas
  - Snowlines

Orbulina universa
Foraminiferal species distributions mapped with core-top analyses
Factor Analysis (Transfer function)
Imbrie and Kipp (1971)

- **Assumption**: modern foram species distributions through space simulate past variations in time
- **End member “factors” are found** (which foraminifera tend to occur with each other).
  A=tropical B=subtropical C=subpolar D=polar X=gyre margin
- All data are assumed to be linear mixtures of these factors. The degree of contribution of an assemblage to a sample is called its “factor loading” with respect to that assemblage.
- A multivariate linear regression is developed between factor loading and temperature
  \[ Tw = 23.6A + 10.4B + 2.7C + 3.7D + 2.0K \] (K=constant)
MODERN

LGM – foram Assemblage “CLIMAP”

B August ocean temperature change (°C)  
Cooling  > 8  6 – 8  4 – 6  2 – 4  0 – 2  
Warming  0 – 2  > 2
Modern Analog Technique

- Simpler than factor analysis
- Compile data base of core tops
- Take your LGM sample and find the modern coretop(s) that it matches the best
- Take the modern temperature from above that core top(s)


Figure 6. Annual mean SST for the Pacific Ocean (a) modern based on gridded data, (b) modern contoured using only LGM sample locations plus control points marked by “C”, (c) reconstructed LGM, (d) anomaly map (LGM minus modern) where plus indicates LGM estimates are within 1°C of modern atlas values. Asterisks on Figures 6a–6c indicate samples which have no modern analogs.
Faunal Techniques

- Significant cooling at high latitudes
- Very little cooling (<2°C) in tropics
- Potential complications
  - Is LGM properly resolved?
  - Does correlation imply causality? Will transfer functions stay the same through time?
  - Dissolution
Foram Oxygen isotopes as a temperature proxy

\[ \delta_{c} - \delta_{w} = 3.28 - 0.20T \]

\[ T = 15.9 - 5(\delta_{c} - \delta_{w}) \]

Epstein (1953)

Glacial-interglacial differences in the δ^{18}O of forams
2-4°C
IF Atlantic surface δ¹⁸O did not change

Billups and Schrag (2000)

Whole ocean δ¹⁸O change (1‰)

Tropical Pacific <2°C
Oxygen Isotopes in Planktonic foraminifera

- Significant cooling at high latitudes (4°C at poleward limit of G. sacculifer)
- Very little cooling in tropics (<2°C in Pacific, perhaps up to 4°C in Atlantic)
- Potential complications
  - Is LGM properly resolved?
  - How well do we know δw (global) or δw (local)?
  - Dissolution

Alkenone Paleothermometer

- Alkenones are long chain organic molecules (C_{37} methyl ketones) produced by coccolithophorids
- There are slight variations in the structure of these organic molecules (degree of saturation)
- The abundance ratio (unsaturation ratio or U_{37}^k is correlated to temperature (demonstrated in lab and field studies)
- Abundance ratio helps control viscosity within cell
UK37 = \[\frac{C_{37:2}}{C_{37:2} + C_{37:3}}\]

Core-top calibration of alkenone proxy

Muller et al. (1998)
Figure 1. Change in annual mean sea surface temperature between the last glacial maximum and the present derived from $U_{37}^{K}$. Modern SST values have been derived from the average $U_{37}^{K}$ values of the last 2000 yrs. If this section was
Alkenone Paleothermometer

- 0-3°C in tropics and subtropics
- Potential complications
  - Different species have different calibrations in the lab ($U_{37}^k$ vs. temperature).
  - Organic matter is very fine and can drift around before being buried.
  - Growth-rate dependence (Popp et al., 1998)

Mg/Ca Paleothermometer

- Mg substitutes for Ca in CaCO$_3$
- Foraminiferal calcite strongly discriminates against Mg relative to inorganic precipitation.
- Mg/Ca in foraminifera increases with increasing T
- Mechanism not well understood
Sediment trap forams, temperature from $\delta^{18}O$ of foraminifera

Anand et al. (2003)

strong dissolution effect on foram Mg/Ca
LGM Mg/Ca reconstructions

- 2-3°C cooling in Tropics
- Method difficult at high latitudes (large T change leads to only small Mg/Ca change)
- Potential complications
  - calibration uncertain
  - dissolution

Noble gasses in Groundwater

![Figure 3-4: The solubilities of various gases in sea water as a function of temperature. The units are standard cubic centimeters of gas contained by a liter of water per atmosphere of pressure exerted by the gas.](image)
need to date your water sample (usually $^{14}$C)

Stute et al. (1995)
- use Ne, Ar, Kr, and Xe (why not He?)

**Fig. 1.** Noble gas temperatures derived from ground water of Holocene age versus today’s mean annual (near-surface) ground temperatures for suitable aquifers in Europe (C: Great Hungarian Plain; Δ: Bunter sandstone, United Kingdom; X: Bavaria, Germany; boxed cross: Kassel, Germany; and ●: Bleichrodt, Germany), South Africa (+: Uitenhage), Brazil (○: Pau), and the United States (■: Comizo aquifer, Texas; ●: Floridan aquifer, Georgia; and ▲: San Juan Basin, New Mexico). Data points represent an average of up to 25 noble gas temperatures derived from ground water of Holocene age for each site (compiled from this study, published data (7, 14), as well as unpublished data). The error in the average noble gas temperature is smaller than the symbol size.
Coral Sr/Ca temperatures

-6°C cooling in tropical Atlantic?
-less in tropical Pacific

Fig. 1. Plot of Sr/Ca ratios in scleractinian corals against the temperature of the seawater from which they grew. The work of Smith et al. (9) is shown by open circles and the dashed line. Results of our work (solid line) indicate that some improvement in this correlation is possible, although the slope and intercept of the resultant linear relation (solid line) are similar to those determined in (9). The error bar for Smith et al. is the average (σx) error. The error bar for our work is ten times the average (σx) error.

Beck et al. (1992)

Fig. 3. Noble gas paleotemperature record derived from the Cashegas (circles) and Sierra Grande (squares) aquifers in Pau Province, northeastern Brazil. Noble gas temperatures are plotted as a function of the ^13C age. The arrows indicate the samples with a ^13C content below the detection limit. Open symbols represent samples obtained during an earlier sampling campaign (1986-1987). The ^13C ages are characterized by an error of a few thousand years because of the uncertainty of the geochemical model.

ΔT = -5.4 ± 0.6°C

Guilderson et al. (1994)

Stute et al. (1995)

Beck et al. (1992)

West Pacific fossil corals, Tudhope et al. (2002)
Ice Core Paleotemperature

- $\delta^{18}$O or $\delta$D in ice
  - Greenland 10-17°C
  - Antarctica 9°C
  - Huascaran, Peru (9°S) 11°C
  - Tibetan Plateau 11°C

- Borehole temperature (diffusion)
  - Greenland 22°C

Snowline Depressions
1 km snowline lowering
Tropical Lapse rate = Moist adiabatic lapse rate = 6°/km
⇒ SST should be 6°C cooler
⇒ exact lapse rate depends on moisture in atmosphere
(dry adiabat = 9.8°C/km)

• In models land does cool more than ocean (1.3x)
• Both data and models suggest that higher lapse rates are possible
• Probably some data is compromised by low sedimentation rates
• Faunal estimates may underestimate change