What do South Atlantic “paleo-density” observations tell us about the LGM overturning circulation?

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Paleo tracers show that the water masses of the Last Glacial Maximum (LGM) were changed, but it is difficult to calculate rates of circulation from these observations.

Recent observations from the LGM along the South Atlantic margins promise to give new insights about the overturning circulation.

Methods of physical oceanography can be applied to paleo-data in much the same way they are used for modern observations.

What do the $\delta^{18}O$ measurements tell us about the overturning circulation? Can we conclusively identify differences between the modern and paleo-circulation?
δ^{13}C tells us about water mass distributions but little about rates of transport.

∇ \cdot (u\delta^{13}C) \approx 0

Curry and Oppo, 2005

δ^{13}C = ^{13}C/^{12}C
Idealized inverse problem: 3 level box model (Huybers, Gebbie, Marchal, in press, J. Phys. Oceanogr.)

Inversion of $\Delta^{14}C$ alone gives a poor estimate of the circulation.

**Paleo-tracers must:**
1. have a well-paced clock
2. be accurate enough
3. work in concert with other tracers
δ¹⁸O as a “paleo-density” tracer

δ¹⁸O_{calcite} = f( δ¹⁸O_{water}, T) 
= δ¹⁸O_{water} + aT' + c

(a, c determined by chemistry of calcification)

δ¹⁸O_{water} = bS' + d  (empirical)

Linearized Eq. Of State:
ρ = α(z) T' + β(z) S' + Ω(z)
Density along the margins is important because of *thermal wind balance*.

Geostrophic balance + hydrostatic balance = thermal wind balance

\[
\frac{\partial v}{\partial z} = - \frac{g}{\rho_0 f} \frac{\partial \rho}{\partial x}
\]

The transport through a rectangle can be calculated by integrating over \(x\) and \(z\):

\[
V(x_1, x_2, z_1, z_2) = -\frac{g}{\rho_0 f} \int_{z_1}^{z_2} \int_{z_1}^{z'} (\rho(x_2, z) - \rho(x_1, z)) \, dz' \, dz + V_0
\]

The geostrophic transport only depends upon the endpoints, \(x_1, x_2\).

Unknown constant \(V_0\).

Equation not valid if the sea floor is encountered.
South Atlantic observations: $\delta^{18}O_{\text{calcite}}$


Red: African margin
Black: S. American margin
Overview: use modern methods to see what the $\delta^{18}O_{\text{calcite}}$ data require (following the inspiration of LeGrand and Wunsch, 1995).

Can we determine that the LGM South Atlantic overturning circulation was different than present?

1. Formulate as an inverse problem
2. Find a modern reference circulation
3. Is the Holocene $\delta^{18}O_{\text{calcite}}$ data consistent with the modern circulation?
4. Null hypothesis, $H_0$: The LGM $\delta^{18}O_{\text{calcite}}$ data are consistent with the modern circulation. Can the null hypothesis be rejected?
Steady-state Geostrophic Model

\[
(v_{i,k+1} - v_{i,k}) \Delta x + \frac{g \Delta z}{\rho_0 f} (\rho_{i+1,k} - \rho_{i,k}) = n_{tw}
\]

Mass cons. \[ \sum_{k=1}^{z_2} \sum_{i=x_1}^{x_2} v_{ik} \Delta x \Delta z = V_{ekman} + V_{bering} + n_m \]

Eq. of state \[ \rho = \rho_0(z)(1 + \alpha T' + \beta S') \]

2100 constraints
6346 state elements

\[ x = \begin{bmatrix} T | S | v \end{bmatrix} \]
\[ n_1 = \begin{bmatrix} n_{tw} | n_m \end{bmatrix} \]
\[ A x + n_1 = 0 \]

Mass conservation necessary to resolve reference level problem
Adding observational constraints to the model

e.g., $\delta^{18}O_{\text{calcite}} = aT' + bS' + c + d$, \(a=0.22 \text{ per mil/ deg C, } b=0.5 \text{ per mil}\)
a, b assumed constant in time, (c+d) takes up the mean offset between LGM, Holocene

All observations can be written as a linear constraint.

$$Ex + n_2 = y$$

The dynamical and observational constraints are combined into one system:

$$E^*x + n^* = y^*$$

$$E^* = \begin{bmatrix} A \\ E \end{bmatrix} \quad n^* = \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad y^* = \begin{bmatrix} 0 \\ y \end{bmatrix}$$

Use the Gauss-Markov method to find the solution $x$ whose dispersion about its true value is as small as possible, subject to the prior information:

$$R_{xx}(r_i, r_j) = \langle x(r_i)x(r_j)^T \rangle \quad R_{nn} = \langle nn^T \rangle$$

$R_{xx}$ is a full matrix which expects a smoothly varying solution, and $R_{yy}$ is based upon observational uncertainties.
Modern South Atlantic Observations: T, S, $\delta^{18}O$ (Hydrobase2, R. Curry)

6312 constraints
6346 state elements
(but there is prior information about each equation and solution element)
Modern density and Holocene $\delta^{18}O$

This solution is consistent with the expected statistics:

$$\mu = <n> = 0$$

$$\sigma = \sqrt{\text{diag}(<nn^T>)} = 0.2 \text{ per mil}$$
Estimated modern reference circulation

Error bars are optimistically small because only small deviations from thermal wind balance are allowed.

Max overturning: 22 Sv ± 3 Sv
Comparison to other modern estimates

26 N, Atlantic Ocean, ECCO state estimate

Figure 5: 12-year mean velocity from the constrained model. Blue areas are flowing southwards. Note that the flow boundaries do not have a simple connection with the water mass structure, even after 12-years of averaging. An Antilles Current and a weak deep western boundary current are visible.

A modification to the reference circulation

Comparison to LGM must account for 120 m sea level change.

Right: Modern density structure, LGM bathymetry

Max overturning: $18 \pm 2 \text{ Sv}$
Assessing the null hypothesis

Null hypothesis, $H_0$: LGM $\delta^{18}O$ are consistent with the modern circulation.

Constrain the solution to:

1. Satisfy the modern meridional transport profile within the modern uncertainty.

2. Satisfy the LGM $\delta^{18}O_{calcite}$ observations.

3. Smoothly vary in space and have reasonable $T, S, v$ values.

Does a solution exist?
Assessing the null hypothesis

Null hypothesis, H₀: LGM δ¹⁸O data are consistent with the modern circulation. NOT REJECTED.
Assessing the null hypothesis

Null hypothesis, $H_0$: LGM $\delta^{18}O$ data are consistent with the modern circulation. NOT REJECTED.

Right panel: Change in modern transport required.
Assessing the null hypothesis

Null hypothesis, $H_0$: LGM $\delta^{18}O$ data are consistent with the modern circulation.

It's unclear if the results are affected by the vertical resolution and scatter in the data.

To resolve this issue, consider a fully-resolved, smoothed version of the data set created with a third-order polynomial.
Assessing the null hypothesis

Null hypothesis, $H_0$: LGM $\delta^{18}O$ data are consistent with the modern circulation.

The null hypothesis can not be rejected with these observations alone.
How are the paleo-observations consistent with the modern circulation?

O18 gradient is reversed, but density gradient is unchanged.
How are the paleo-observations consistent with the modern circulation?

Are the changes in water-mass properties plausible?

The water-mass changes can not be immediately ruled unrealistic.
What additional data are necessary to reject the null hypothesis?

An independent constraint on temperature or salinity is necessary.

Suppose Mg/Ca measurements of temperature are available for all the sediment cores of this study.

With the assumption that LGM temperatures are changed by less than 1 deg C, the null hypothesis can be rejected.
Conclusions

δ^{18}O observations alone do not require the LGM overturning circulation to be different from the modern circulation.

The δ^{18}O observations are inadequate because an additional constraint is needed for temperature or salinity.

In the case that temperature measurements are available at the core sites, it appears possible to reject the null hypothesis.

Paleo-temperature or salinity measurements would be extremely valuable. Another avenue of future research would be the inclusion of additional dynamical constraints to further interpret the observational database.