Circulation scenarios for explaining the LGM $\delta^{13}C$ sediment-core data

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INTRODUCTION

A number of lines of evidence point to a changed Atlantic circulation during the Last Glacial Maximum[e.g., 1-3], but previous inverse modeling studies found that paleo-observations are not sufficient to distinguish between the modern and LGM circulations[e.g.,4-5]. Here I extend the TMI method[6] to model modern-day and glacial $\delta^{13}C$ at 4° horizontal resolution and 33 vertical levels. Can the LGM $\delta^{13}C$ sediment-core data be explained without changing the modern-day water-mass distribution? What does this imply for changes in the LGM circulation relative to the modern-day?

TMI INVERSE METHOD

TMI is trained with modern-day temperature, salinity, $\delta^{18}O$, phosphate, nitrate and oxygen to diagnose the complete set of water-mass pathways in the WOCE-era (1990's) ocean and the nonconservative effects of biological activity. Using the previously-solved pathways matrix **A**, relating phosphate remineralization to interior $\delta^{13}C$ sinks (in a vector **d**), and supplying surface boundary conditions (also included in **d**), it is possible to predict the global $\delta^{13}C$ distribution by solving the equation **Ac=d**.

Null hypothesis: The $\delta^{13}C$ data can be fit within its uncertainty with the modern-day water-mass distribution.

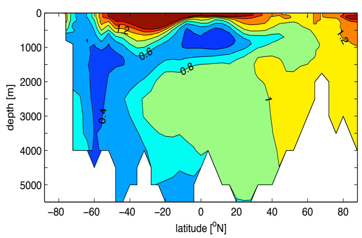
Find the best fit to the data by solving a least-squares problem:
Minimize a sum of squared misfits, $J = (\mathbf{Ec}-\mathbf{c}_{obs})^T (\mathbf{Ec}-\mathbf{c}_{obs})$, where **E** maps the modeled field onto the observations, subject to the constraint **Ac=d**, where **d** (the control vector) is allowed to vary. Previously, investigators found that the null hypothesis could not be rejected.

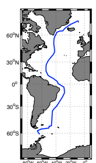
SUMMARY

- The LGM $\delta^{13}C$ sediment-core data cannot be explained by changing surface boundary conditions on $\delta^{13}C$, the global rate of circulation, or surface productivity patterns, supporting the notion the glacial water masses must have been distributed differently than the modern day.
- If the LGM ocean is well-approximated by a steady state, the changed water-mass distributions imply a change in oceanic mass transport fields.
- The TMI inverse model allows the null hypothesis to be rejected, whereas traditional inverse models do not, due to the explicit water-mass pathways information that is at the heart of the method.

MODERN-DAY TEST CASE

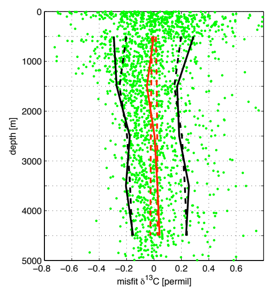
The first test is whether the modern-day $\delta^{13}C$ is consistent with the TMI pathways, as TMI was not trained with $\delta^{13}C$. Here, I use 1,998 data points of seawater $\delta^{13}C$ from GEOSECS. The same null hypothesis is formed, with the GEOSECS data as the reference in the sum of squares, and the surface boundary conditions for modern-day $\delta^{13}C$ being the control variable that is effectively being solved for. In this case, the null hypothesis is true, and if the $\delta^{13}C$ is consistent with the TMI pathways, then it will not be rejected. The purpose of this test is to be sure that the test is not susceptible to false rejections.

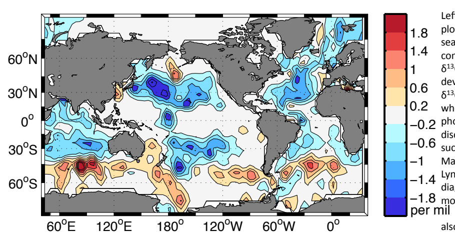




Far left panel: Meridional section of the best fit modern-day $\delta^{13}C$ distribution along the western Atlantic GEOSECS ship track (left panel). The TMI pathways effectively serve as a type of mapping function or interpolator that is consistent with the advection-diffusion properties of a steady-state fluid.

Right panel: Evaluating the hypothesis test and goodness of fit of the solution. Each green dot corresponds to the misfit between the estimate and the data, collapsed to a function of depth. Red dashed lines indicate the acceptable range of the mean misfit according to the 95% confidence limits of a 2-sided z-test, and the red solild line is the actual mean misfit as calculated in 500 meter bins. Black dashed lines give the expected one standard-deviation range according to measurement error estimates, and the solid black lines give the actual one standard-deviation range of the misfit. Visually, the dashed and solid lines are roughly co-located, suggesting consistency between the data and estimate. Statistically, the J value and the p-values of the z-tests confirm that the null hypothesis cannot be rejected. The TMI pathways pass the first test, that a tracer field that was withheld during the training of the method can be simulated. Furthermore, the assumed relationship between nutrient cycling and the nonconservative effects on $\delta^{13}C$ is reasonable within the errors of the data.

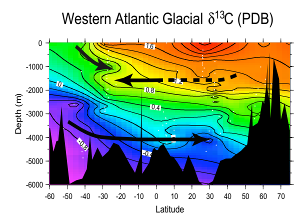


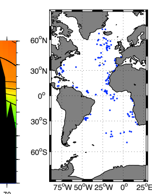


Left panel: Diagnostic plot of $\delta^{13}C_{as}$, the air-sea effect on surface concentrations of $\delta^{13}C$, defined as the deviation from $\delta^{13}C = 2.7 - 1.1\,P$, where P is dissolved phosphate, as discussed by authors such as Broecker, Maier-Reimer, and Lynch-Stieglitz.Other diagnostics of modern-day $\delta^{13}C$ are also possible.

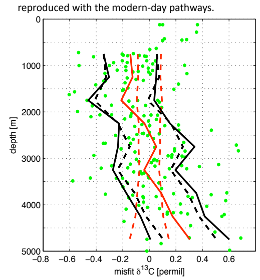
LGM SCENARIO 1: SURFACE $\delta^{13}C$ CHANGES ONLY

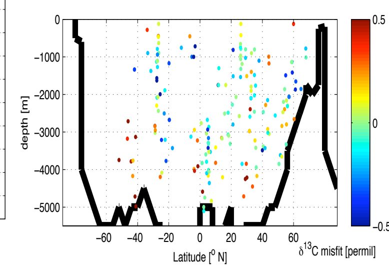
Can the LGM $\delta^{13}C$ sediment-core data be explained by simply changing the surface boundary conditions for $\delta^{13}C$ (without any change in water-mass pathways)? Here I use 184 data points from a multitude of Investigators (Bill Curry, personal communication, see right panel for locations and objectively interpolated map of LGM $\delta^{13}C$ from Curry and Oppo 2005). I allow changes in the part of the vector **d** that corresponds to the surface boundary conditions. The steps of the null hypothesis test used in the modern-day test case are now repeated for "LGM scenario 1".

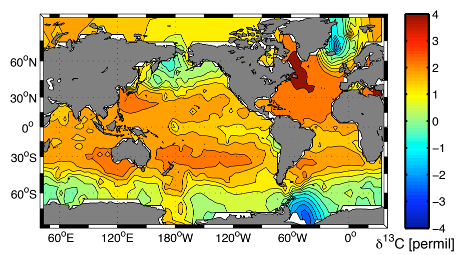




Left panel below: Statistics of the null hypothesis test, in the same form as the figure in the lefthand column. The solid red line (mean misfit as a function of depth) shows that the estimate is systematically too negative near the surface and too positive at depth. At 6 of 9 depth bins, the null hypothesis can be rejected with p-value < 0.05 (5% insignificance level).
Right panel below: The misfit between the estimate and sediment-core observations, plotted as a virtual meridional section through the Atlantic Ocean. The proper gradient between low- $\delta^{13}C$ southern-origin waters and high-$\delta^{13}C$ northern-origin waters cannot be reproduced with the modern-day pathways.



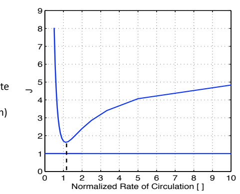


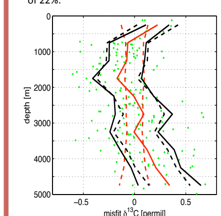


While the statistics tell that the LGM $\delta^{13}C$ estimate is invalid, it is instructive to consider how the method attempted to change the surface $\delta^{13}C$ in order to best fit the observations (left panel). The large vertical gradient requires a large horizontal surface gradient, which is likely too large to be realistic. In addition, lower NADW from the Greenland Sea is given $\delta^{13}C$ values that are similar to AABW values from the Weddell Sea. The very high $\delta^{13}C$ values of the Labrador Sea are probably enough to reject this solution as being unrealistic.

LGM SCENARIO 2: GLOBAL SLOWDOWN

Can the LGM $\delta^{13}C$ sediment-core data be explained by changing the surface boundary conditions for $\delta^{13}C$ and by allowing a uniform global change in circulation rate (without any change in water-mass pathways)?
In this LGM scenario 2, the formulation follows LGM scenario 1, but an additional variable to estimate is the global circulation rate (normalized with modern-day=1). The global circulation change that best fits the data (right panel) is a speedup (not a slowdown) of 22%.

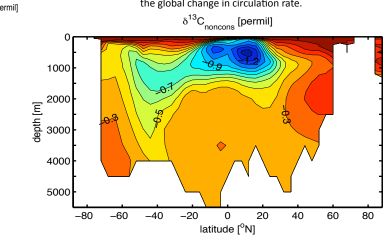




Even with this additional degree of freedom, no acceptable solution is found according to the J values being greater than 1 for all circulation values, and the statistical tests on the misfit (see left, in same format as misfit plots in previous columns). The null hypothesis is again rejected.

Below: Modern-day nonconservative part of $\delta^{13}C$ as diagnosed by TMI. The global circulation rate variable affects the size of this perturbation in the ocean interior. A globally uniform change in productivity cannot be distinguished from the global change in circulation rate.

While no acceptable solution is found, the optimized speedup of 22% can still be interpreted. This perturbation makes the intermediate-depth tropical $\delta^{13}C$ less negative, leading to a better fit with the sediment core data. While changes in the circulation rate can help explain the upper and mid-depth ocean, it doesn't provide a means of explaining the deep ocean at the same time.



LGM SCENARIO 3: PRODUCTIVITY CHANGES

In LGM scenario 3 (not pictured), I ask whether changes in the surface pattern of productivity can explain the $\delta^{13}C$ data. The interior $\delta^{13}C$ data can be fit provided that large (10 times modern-day productivity) and localized perturbations are allowed. Such surface changes are unrealistic, and thus the null hypothesis can be rejected. As none of the increasingly-complex LGM scenarios have been able to explain the $\delta^{13}C$ data in a realistic way, it is clear that changes in water-mass distributions between the LGM and modern-day must have occurred, and they are important for explaining the differences in observed $\delta^{13}C$.

REFERENCES

1. McManus et al., *Nature,* 2004. 2. McCave et al., *Nature,* 1995. 3. Lynch-Stieglitz et al., *Nature,* 1999. 4. Legrand & Wunsch, *Paleoceanogr.,* 1995. 5. Huybers et al., *JPO,* 2007. 6. Gebbie et al., *JPO,* 2010. I thank Peter Huybers, Carl Wunsch and NSF for support, and the multitude of investigators who have provided their data. Manuscript available upon request.