Connecting Atmospheric Dynamics to Abyssal Ocean Geometry on Paleoclimate Time Scales

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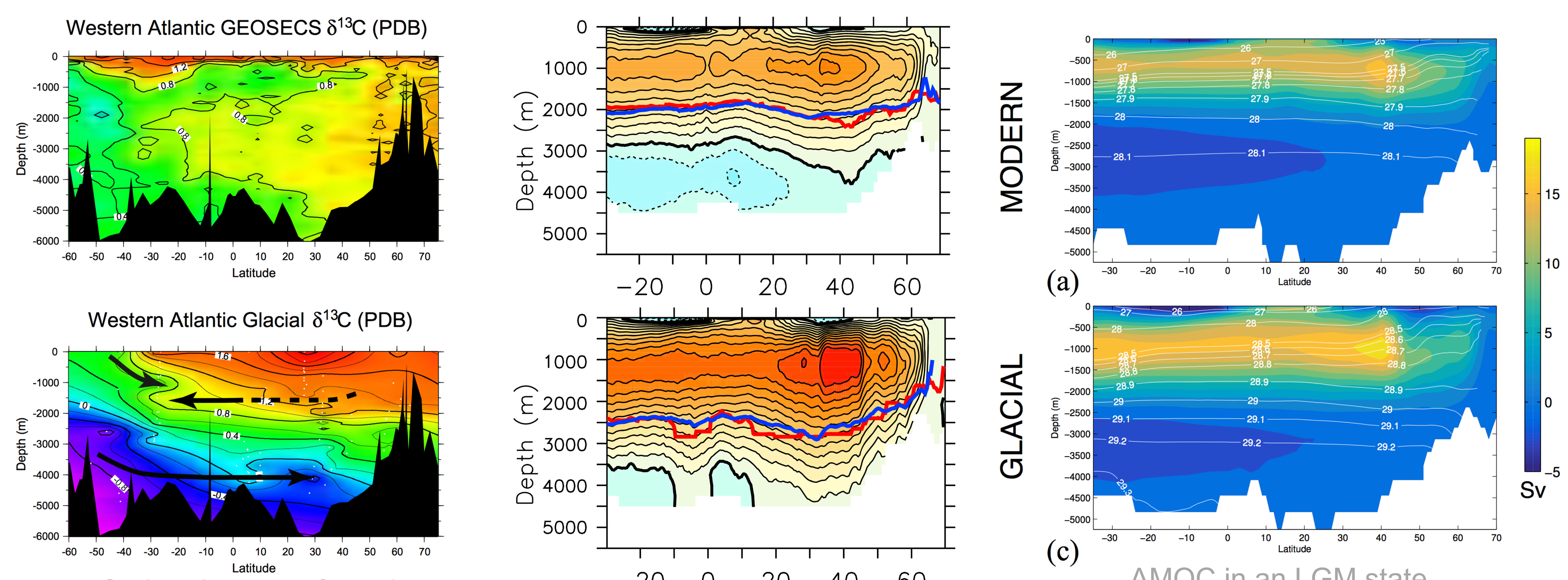
Motivation: Estimating past ocean states using models + data



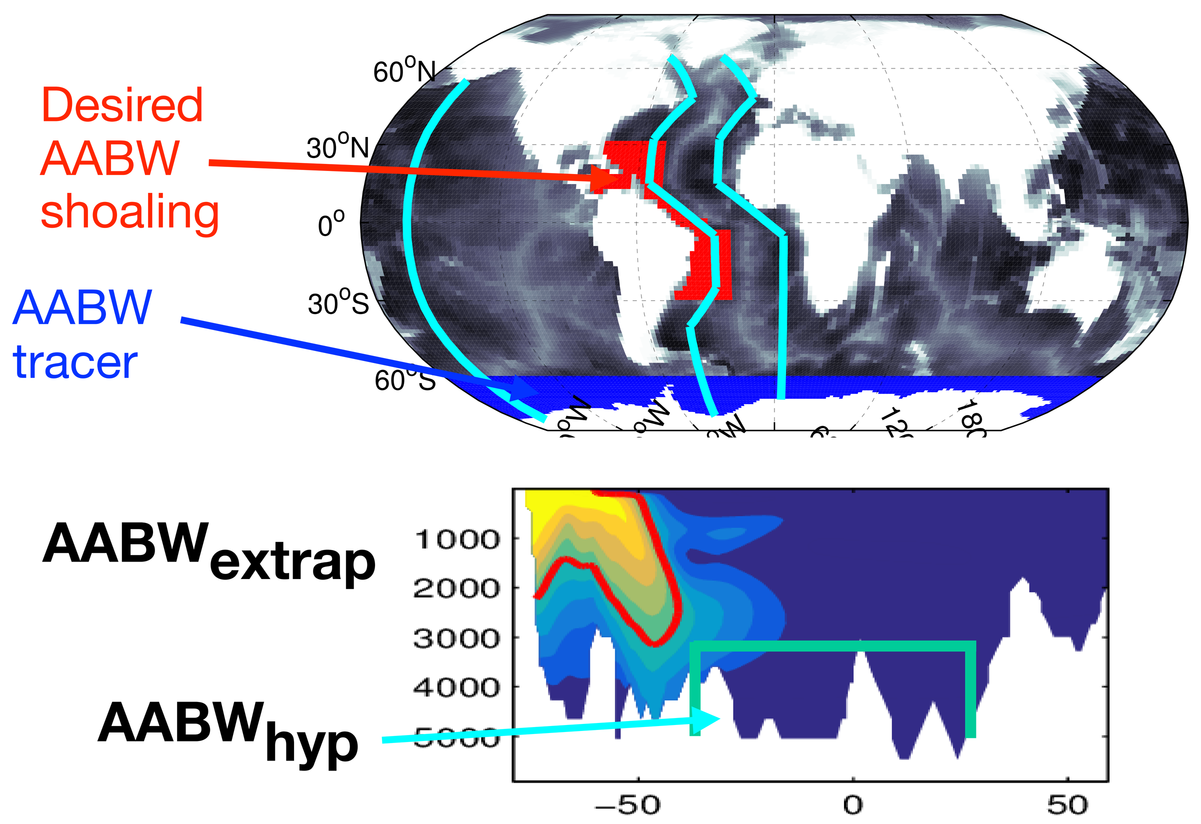
Carbon isotopes from the Westen N. Atlantic (Curry and Oppo 2005)

PMIP3 PI (top) and LGM AMOC streamfunctions (Muglia and Schmittner 2015)

AMOC in an LGM state estimate (Amrhein et al., 2018) is stronger and deeper than in the modern

An LGM state estimate finds a deeper, stronger AMOC upper cell and less AABW, contrary to tracer data. Can we identify mechanisms to change abyssal geometry that are consistent with both ocean and atmosphere dynamics?

How can the atmosphere most effectively change the abyss?



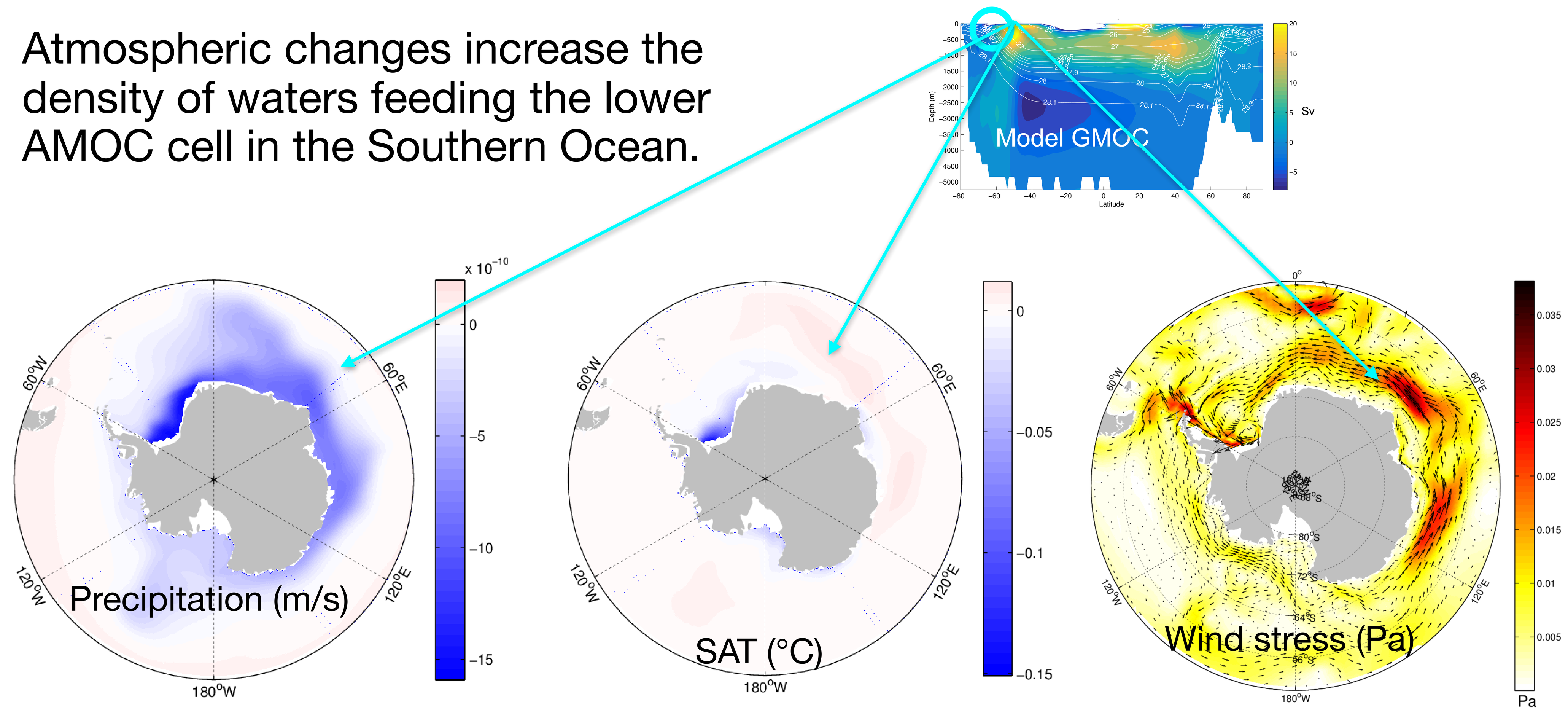
Integrate 2°x2° MITgcm under modern conditions with an AABW tracer and compute the cost function

$$J = \left(\mathbf{AABW_{extrap}} - \mathbf{AABW_{hyp}}\right)^2$$

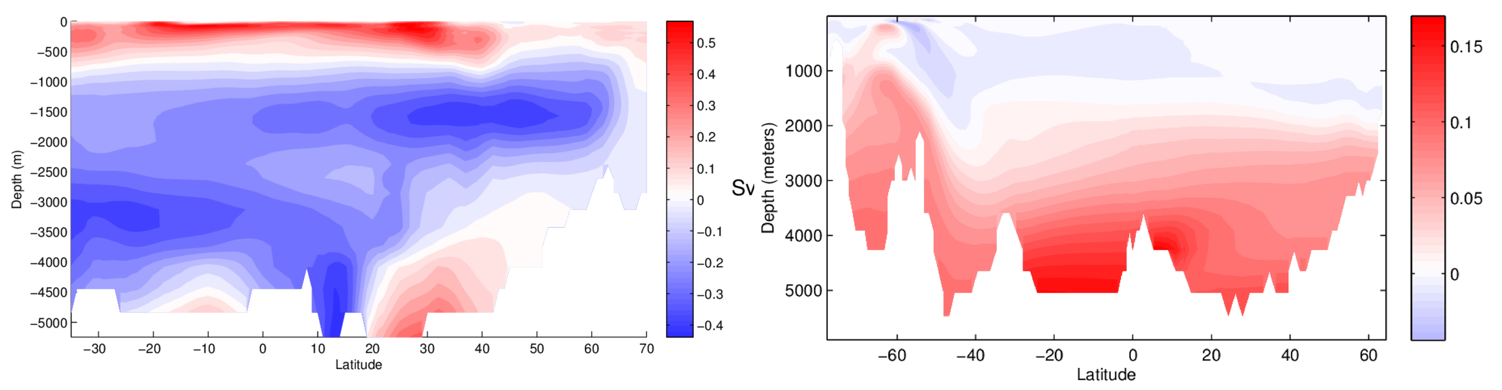
Adjoint sensitivities show patterns of control variables **u** (wind stress, SAT, and precipitation) that increase AABW

$$\mathbf{s} = \partial J / \partial \mathbf{u}$$

Atmospheric changes increase the density of waters feeding the lower AMOC cell in the Southern Ocean.



Integrating under perturbations increases AABW and strengthens (weakens) lower (upper) AMOC cells.



Attributing AMOC and abyssal geometry changes to atmospheric dynamics

How can we connect likely atmospheric dynamics to past changes in ocean geometry?

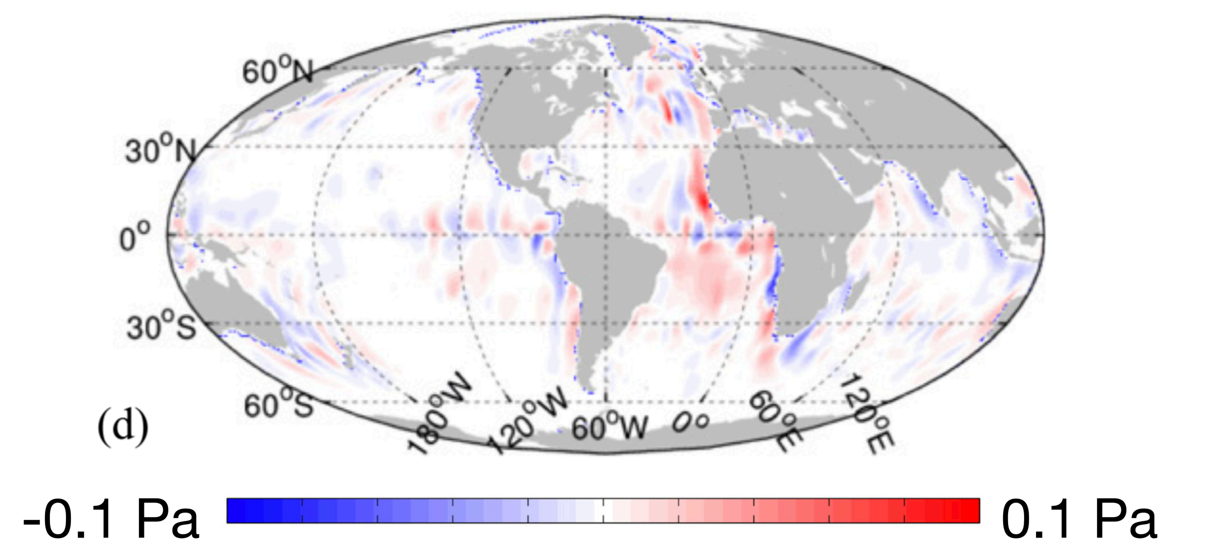
Approach: Find **filtered sensitivities** that reflect statistics of atmospheric uncertainties and/or variability.

One test: How could changes in interannual atmospheric SAT variability most imprint the abyss?

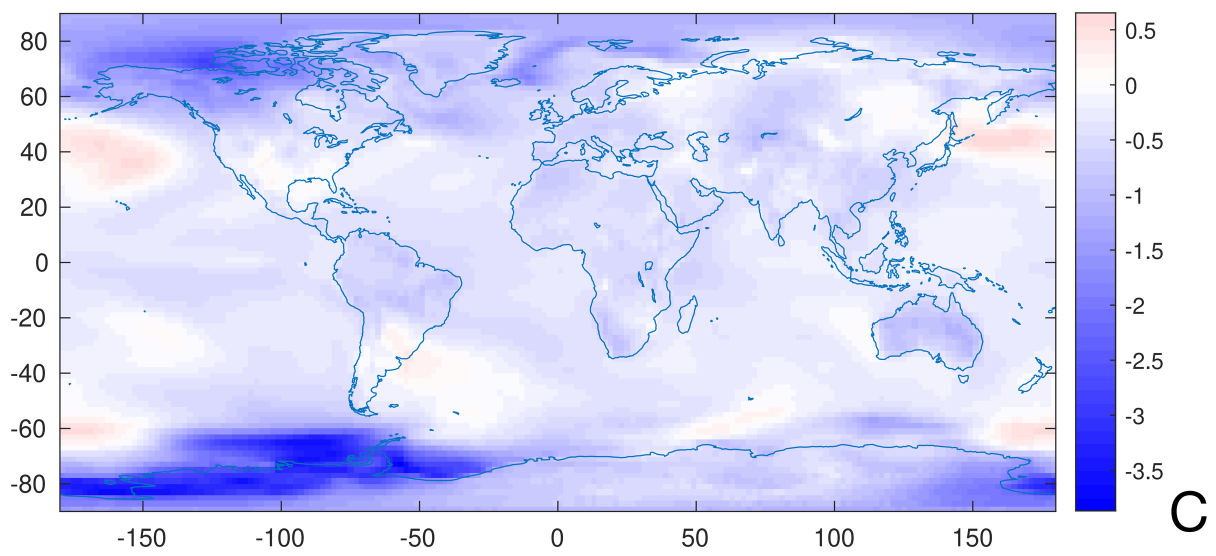
Estimate $\mathbf{B} = \langle \mathbf{u}\mathbf{u}^\top \rangle \approx \mathbf{X}\mathbf{X}^\top$ from annual-mean CCSM4 SAT anomalies, then solve:

$$J_a = \mathbf{s}_a^\top \mathbf{B}^{-1} \mathbf{s}_a + \lambda(\mathbf{s}_a^\top \mathbf{s} - \alpha)$$

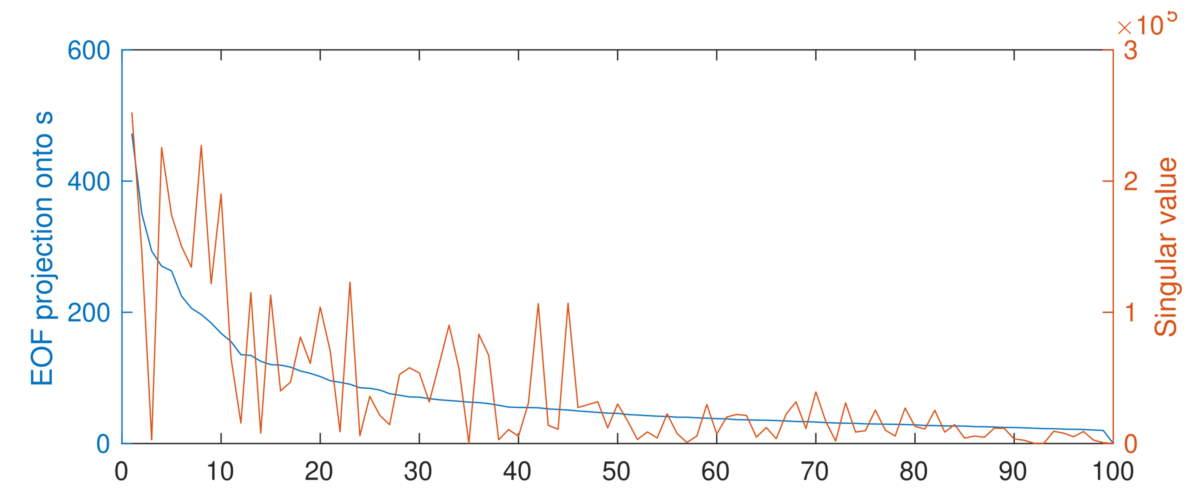
$$\mathbf{s}_a = \frac{\alpha}{\mathbf{s}^\top \mathbf{B}\mathbf{s}} \mathbf{B}\mathbf{s}$$



τ_y anomaly inferred by Amrhein et al. (2018). Can the atmosphere really do this?



SAT sensitivity pattern "filtered" by atmospheric dynamics. The (CCSM4) atmosphere can do this! But this optimal pattern accounts for only a small fraction of the LGM-modern geometry change.



Some atmospheric EOFs contribute disproportionately to ocean changes

Conclusions, challenges, opportunities

Results (under draconian assumptions of stationarity and linearity) suggest changes in internal variability do not suffice to switch the sign of glacial-interglacial AMOC depth and strength.

Filtered ocean sensitivities permit dynamically sensible adjoint updates.

A central challenge: prior error covariances ($\mathbf{B}$)! What uncertainties should they reflect? How does the picture change if $\mathbf{B}$ reflects *structural modeling and forcing uncertainties* rather than internal variability?

How does *sea ice* mediate atmospheric changes?

Can we construct state estimates that are consistent with atmospheric statistics as a first cut at coupled online paleoclimate data assimilation?

What do these approaches tell us about the connections between ocean and atmosphere variability in the modern North Atlantic?