ECCO-related activities at Harvard

1. Optimal initial conditions calculated by the use of a tangent-linear and adjoint model
(Zanna, Heimbach, and Tziperman)

2. The MOM4 tangent-linear and adjoint project
(ECCO-GODAE)

MOM4_ad

FastOpt

3. Using models and observations to constrain the climate state of the Last Glacial Maximum

PALEO-ECCO

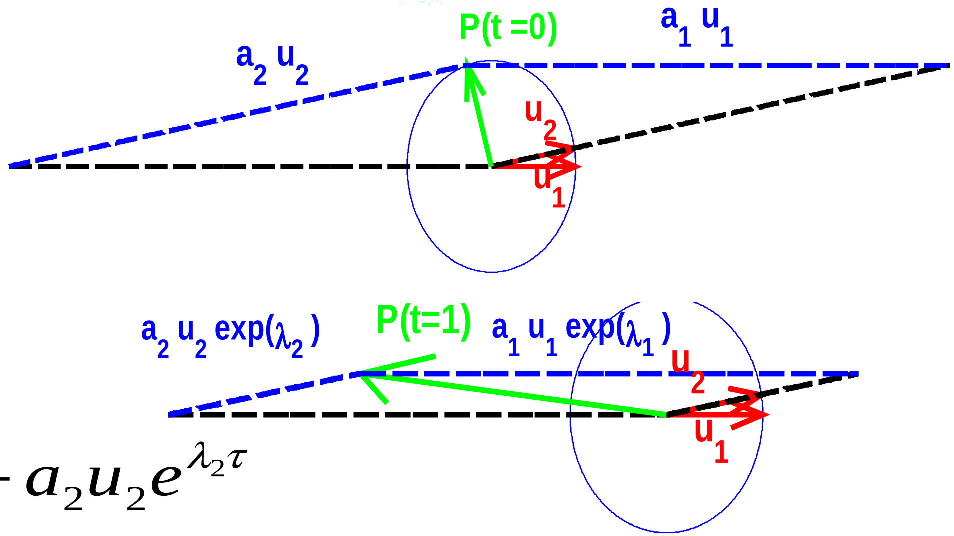
Generalized Stability Theory

Zanna, Heimbach and Tziperman

Stable linear system

$$\frac{dP}{dt} = AP, \quad P \rightarrow 0 \quad as \quad t \rightarrow \infty$$

$$AA^T \neq A^T A$$



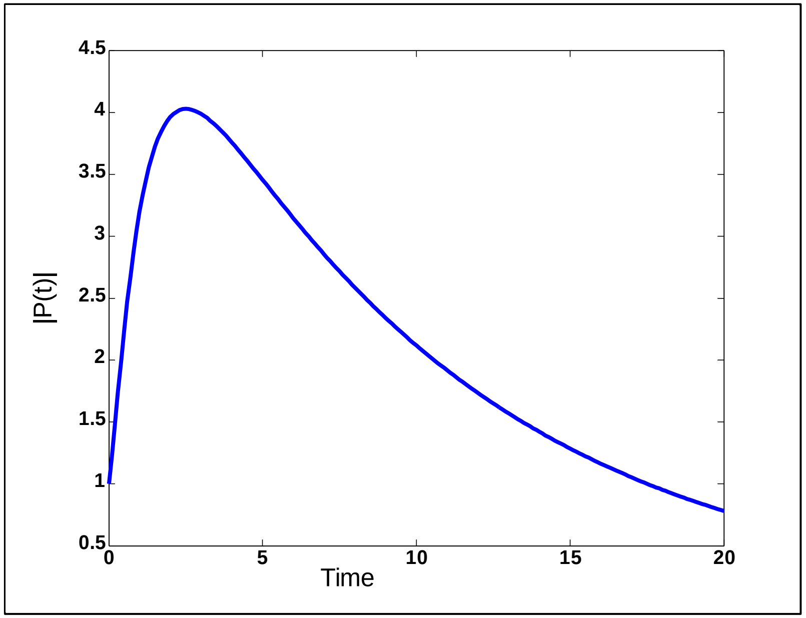
If A is non-normal
then eigenvectors are not orthogonal
→ may lead to transient amplification

(2D) solution at time τ $P(\tau) = a_1 u_1 e^{\lambda_1 \tau} + a_2 u_2 e^{\lambda_2 \tau}$

$$If \ \lambda_2 << \lambda_1 < 0, \ then \ a_2 u_2 e^{\lambda_2} \rightarrow 0 \ quickly$$

$$leaving \ mostly \ P(t=1) \approx a_1 u_1 e^{\lambda_1}$$

$$eventually \quad P(t \rightarrow \infty) \rightarrow 0$$



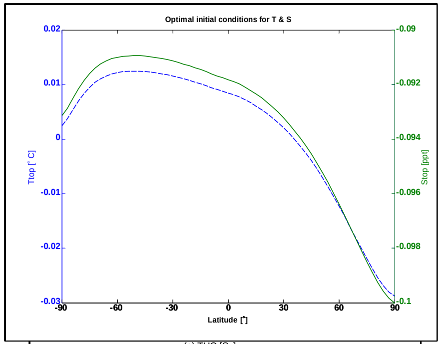
Transient amplification: Interaction of non orthogonal eigenmodes

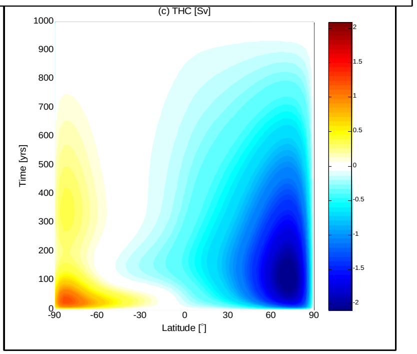
(19) Partial initial cancellation

(20) Different decaying rates

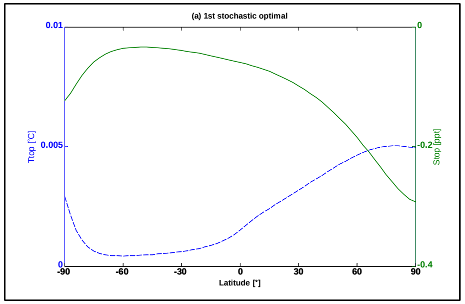
(e.g. Farrell, 1988; Farrell & Ioannou,1996, Trefethen, 1993

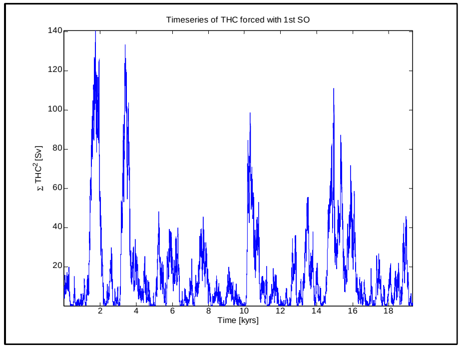
Surface Excitation of the Thermohaline Circulation





- Zonally averaged coupled ocn-atm model
- Optimal i. c. of surface temperature & salinity lead to transient growth of the THC after 120 yrs
- Infinite growth of the THC, T is amplified by a factor of 7, main contribution to the THC is from the deep temperature
- Growth mechanism: interaction of 7 non-orthogonal eigenmodes & advection of mean T & S by the anomalous velocity
- Stochastic Optimal = Spatial structure of stochastic forcing
- which maximally excites the THC variability.

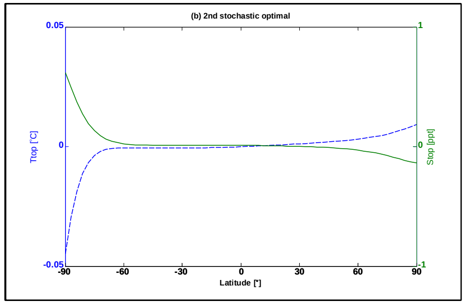


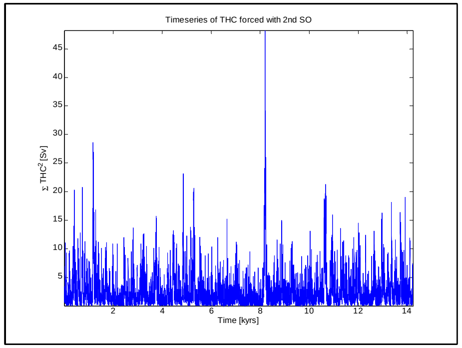


First 2 stochastic optimals: large-scale spatial structures & only S contributes to the density

(a) 1st stochastic optimal explains 22% of the variance & excites modes with relatively long decay timescale

(b) 2nd stochastic optimal explains 4% of the variance & excites modes with shorter decay timescale





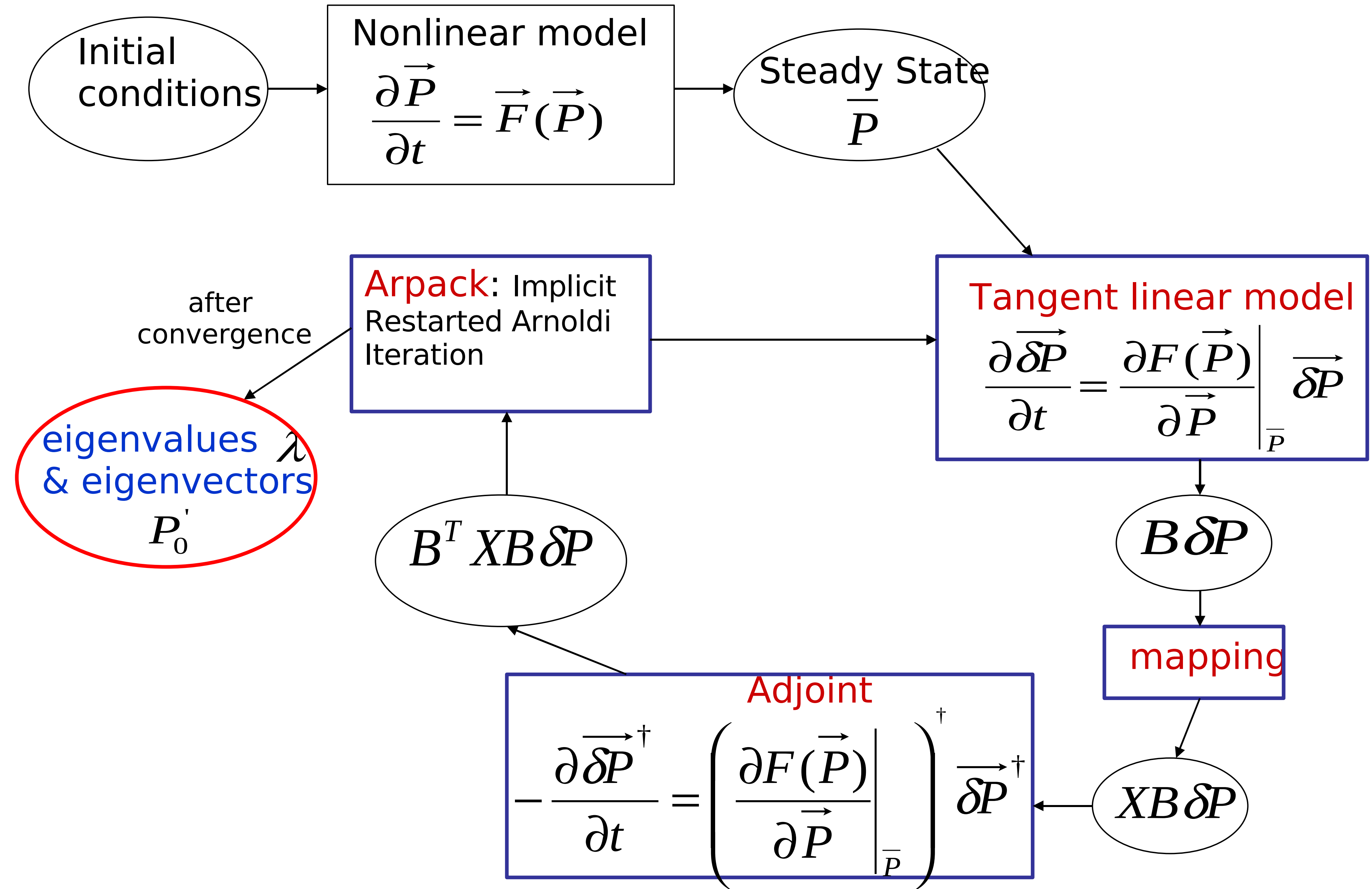
Spectrum is red with no significant peak

(Zanna & Tziperman, JPO, 2005 & 2007)

Procedure

Finding optimal initial conditions with the ECCO/MITgcm code

→ Solving for eigenvectors P_0' and eigenvalues λ of $(e^{A\tau})^T X e^{A\tau} (= B^T X B)$



MOM4 Adjoint Project: TAF Updates for f90

MOM4_ad

TAF has been updated to reach near compatibility with Fortran 90:
TAF 1.8.24 (31 Jan 2006) --> TAF 1.8.82 (present)

TAF issues solved:

- Handling overloaded functions
- Improved use of allocatable arrays, especially “help” arrays
- Correct parsing and modifications of the Flexible Modeling System

Project Status:

TLM: Basic model (complete tracer and momentum equations) completed with less than 5 necessary hand corrections.

ADM: fully nonlinear model with barotropic motions and necessary recomputations. Full suite of active state variables, parallelized.

CVS tree has been incorporated in GFDL main trunk.

MOM4 Adjoint Project: July 2006-June 2007 Timetable

MOM4_ad

Development of a basic adjoint for scientific purposes:

- ★ Heat flux, freshwater flux, wind stress added to the control vector.
- ★ Make density and pressure variables "active"
- ★ Add barotropic dynamics to the TLM
- ★ Add barotropic dynamics to the ADM with recomputations for the fully nonlinear model
- ★ Add baroclinic dynamics to the TLM
- Add baroclinic dynamics to the ADM with necessary recomputations
- Top-level optimization routines

★ = completed 2006
by B. Cheng, T. Lee, G. Gebbie

Optional development:

- Neutral physics packages (KPP, GM, etc.)
- Adjoint of linear statistical atmosphere

MOM4 Adjoint Project: Summary

MOM4_ad

TAF is now compatible with Fortran 90.

F90 advantages: elemental functional form. Array slices.

F90 disadvantages: derived type flow analysis. Active pointers, no preprocessor definitions (MOM4)

The MOM4 adjoint will be used on ENSO-related projects at JPL and Harvard.

An ENSO sensitivity study is set to follow up the forward model calculations of Gebbie et al. 2006, *JAS*, and Gebbie and Tziperman, 2007, in preparation.

An adjoint-based initialization scheme has the potential to break the recent stall in ENSO prediction skill.

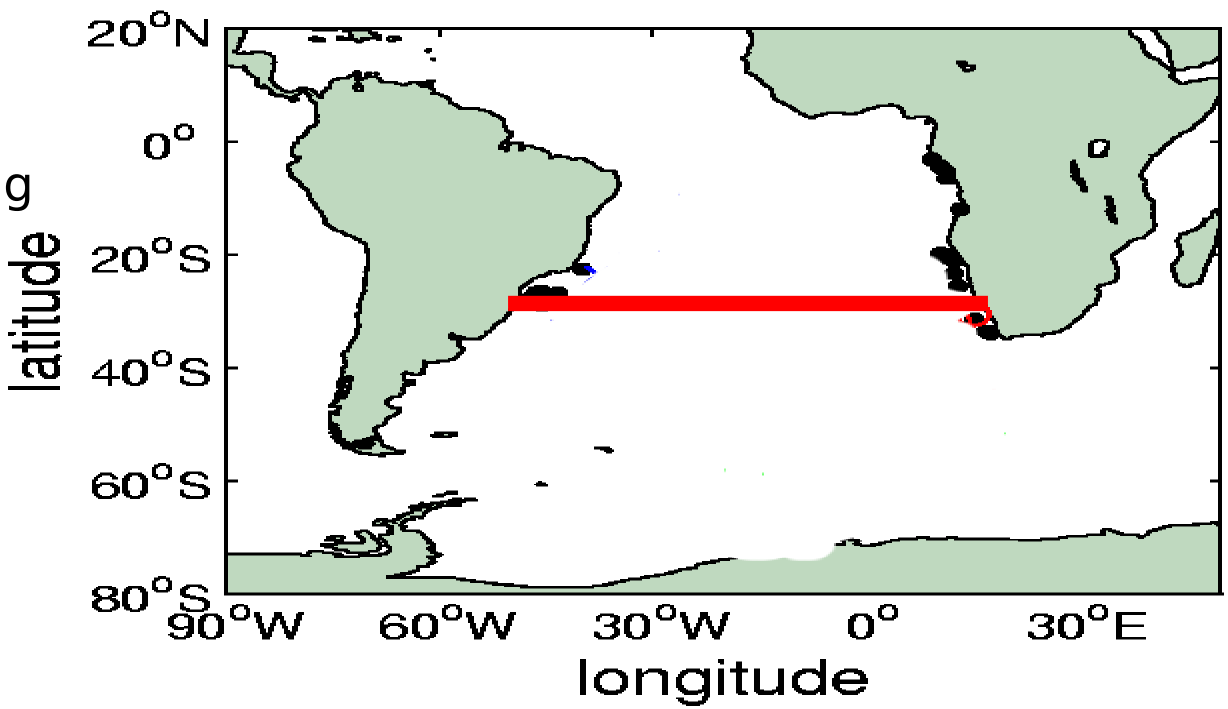
Using inverse methods to estimate the climate of the Last Glacial Maximum

PALEO-ECCO

-- First, recent work shows that the LGM ocean state estimation problem can be formulated as an inverse problem

-- Second, integrating the experiences of ECCO into paleoclimate work is a promising avenue

Given sediment cores in the South Atlantic, what can we say about the overturning circulation during the Last Glacial maximum across 30 S?



LGM Model and Data

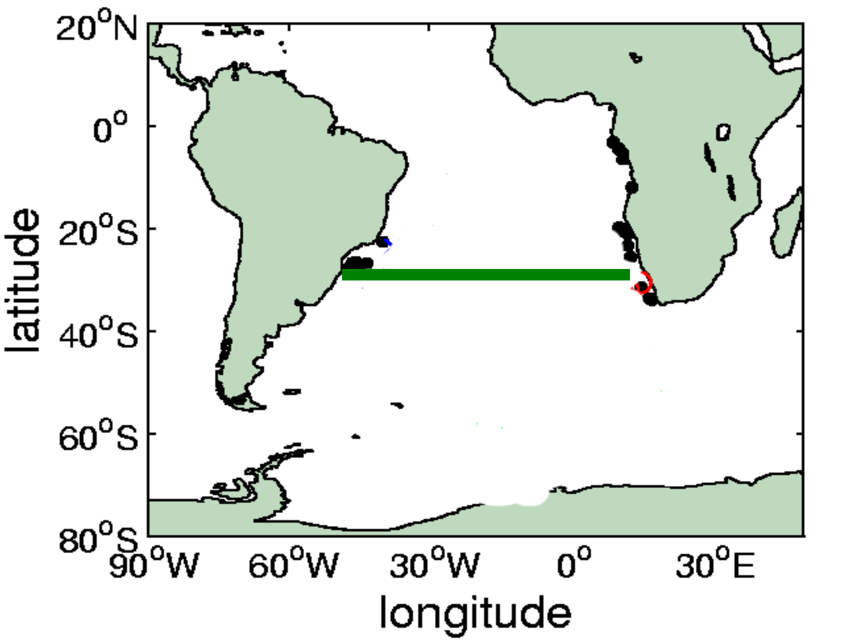
PALEO-ECCO

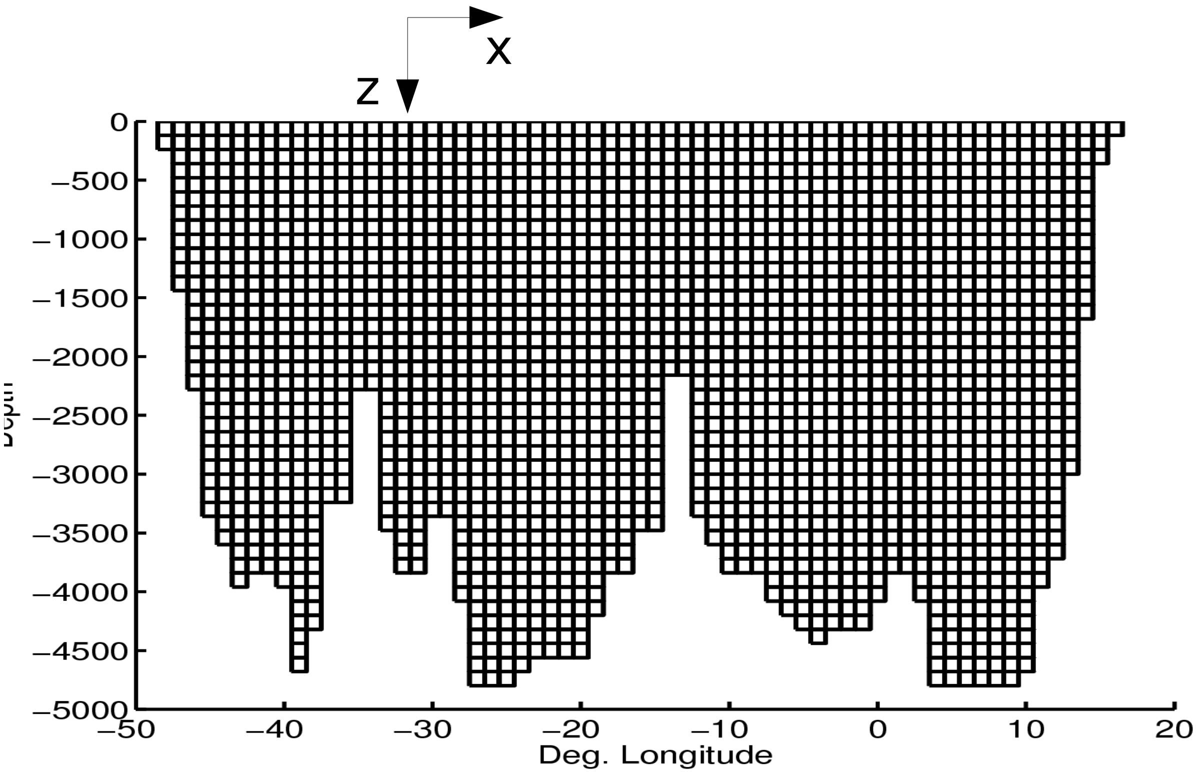
thermal wind $$(v_{i,k+1} - v_{i,k})\Delta x + \frac{g\Delta z}{\rho_o f}(\rho_{i+1,k} - \rho_{i,k}) = n_{tw}$$

conservation of mass $$\sum_{k=z_1}^{z_2} \sum_{i=x_1}^{x_2} v_{ik}\, \Delta x\, \Delta z = V_{ekman} + V_{bering} + n_m$$

equation of state $$\rho = \rho_o(z)(1 + \alpha T' + \beta S')$$

LGM observations $$\delta^{18}O_{calcite} = aT' + bS' + c$$



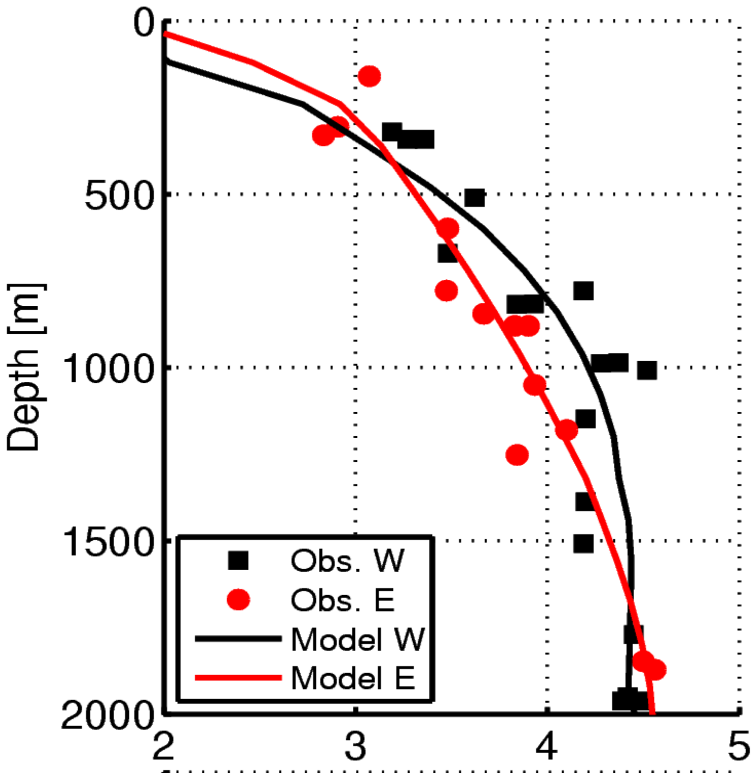


Method

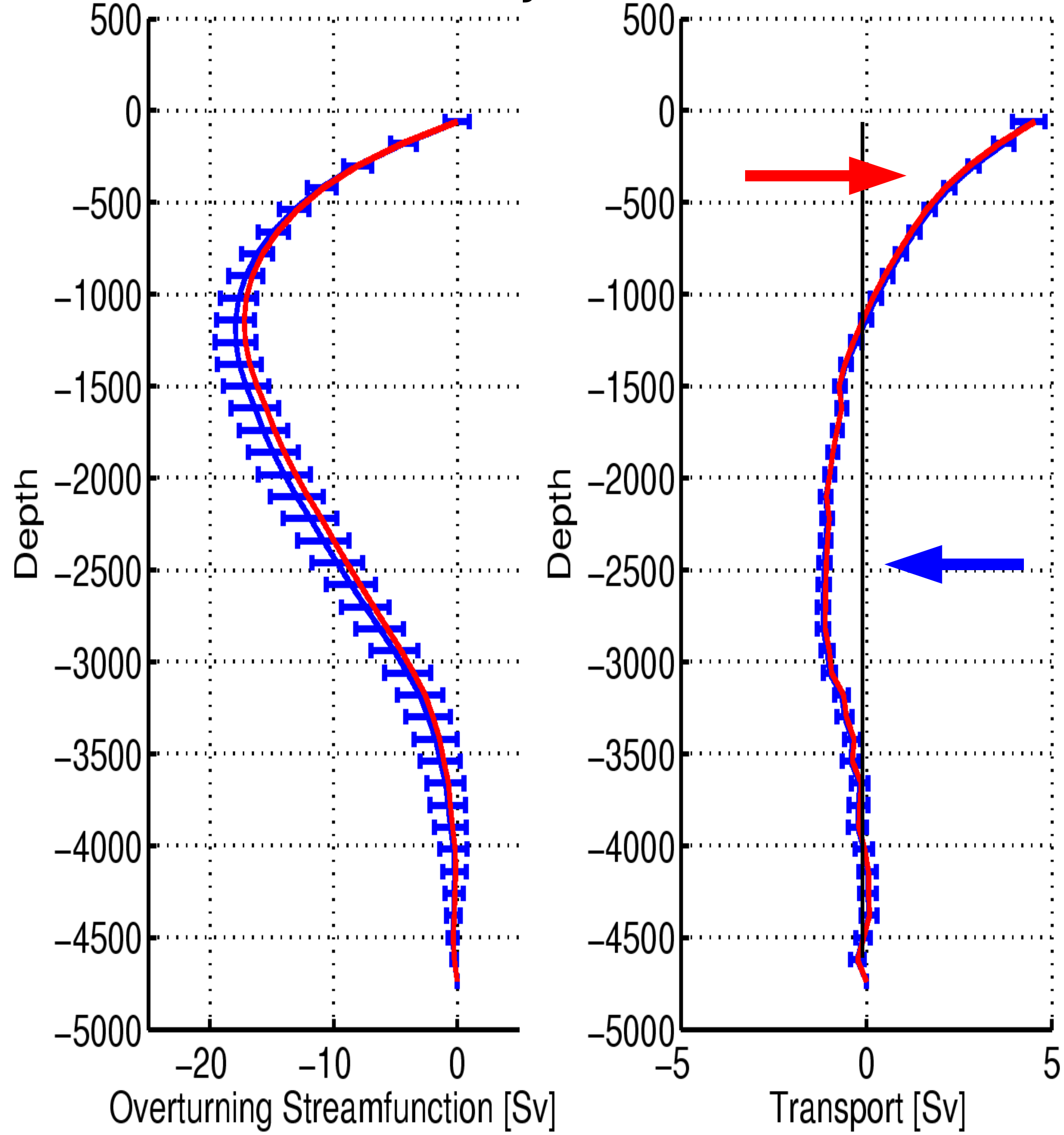
Hypothesis testing in the LGM

H0: The LGM observations are consistent with the modern overturning.
Minimize a cost function which penalizes deviation from these constraints.
A solution is found: The null hypothesis can not be rejected.

LGM $\delta^{18}O_{calcite}$



Modern (blue) and adjusted (red) circulation



Obs.: symbols
Model: solid lines

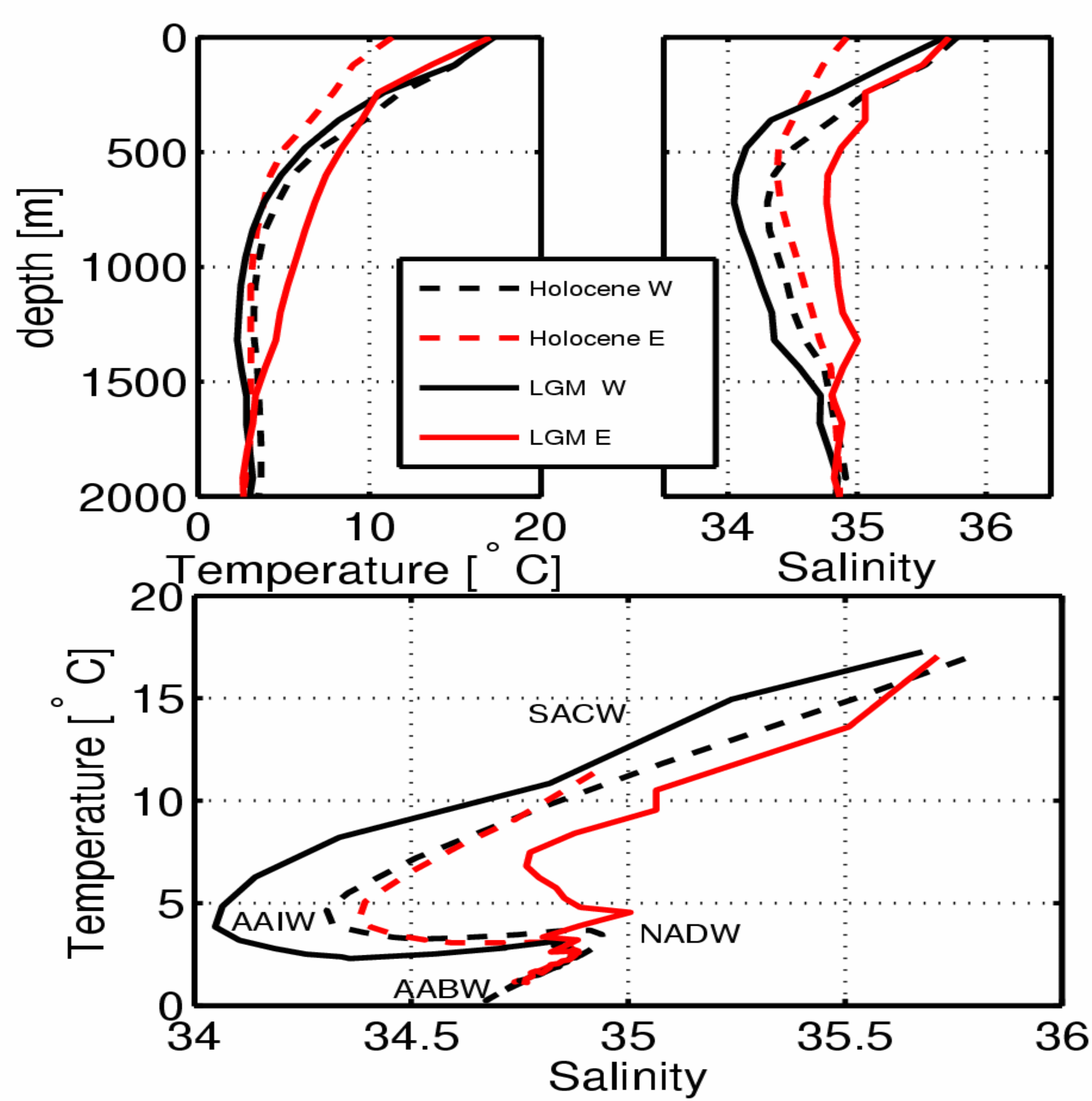
PALEO-ECCO

Points out a loophole not considered by other investigators.

Makes a prediction – changes in T and S.

Calls intermediate water changes.
Sea-ice influence?

Need more complete set of dynamics or further observations: a call to use ECCO system.



PALEO-ECCO

Using the MITgcm/ECCO codes to estimate and understand the LGM climate

1. Must add LGM data types to the ECCO system.

2. Does a first-guess simulation reasonably reproduce the Holocene paleo-data? (A check of consistency).

3. What does a first-guess LGM simulation look like?

4. What components of the model must be improved in order to do a reasonable LGM study?