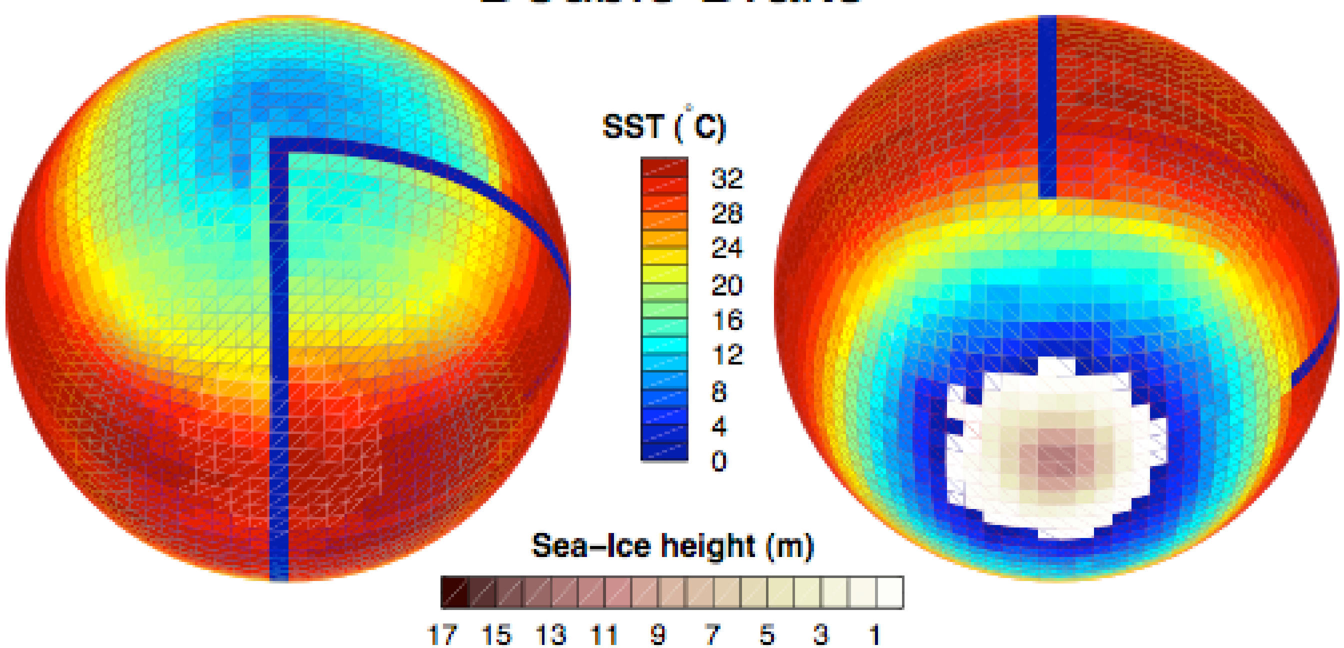
Predictability and non-normal dynamics in models

Ross Tulloch
with John Marshall, Martha Buckley, David Ferreira, and Jean-Michel Campin
MIT

Double Drake



Outline

- Explore predictability of AMOC in models, both simple and complex
- Describe predictability experiments with the MITgcm- Double Drake (DDR)
- Interpretation in terms of non-normal mode dynamics, and comparison of DDR with CM2.1

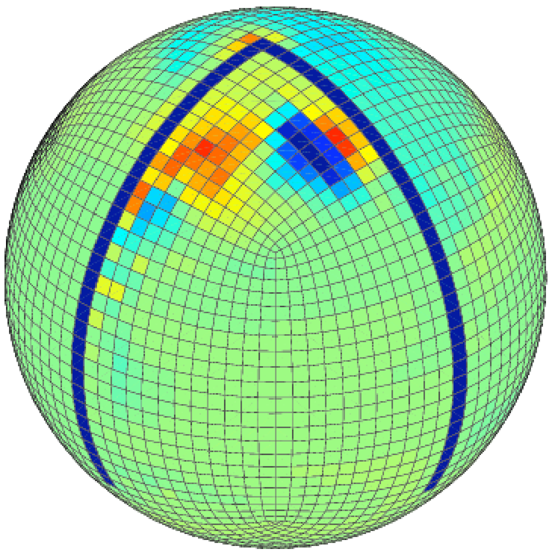
Exploring predictability in models

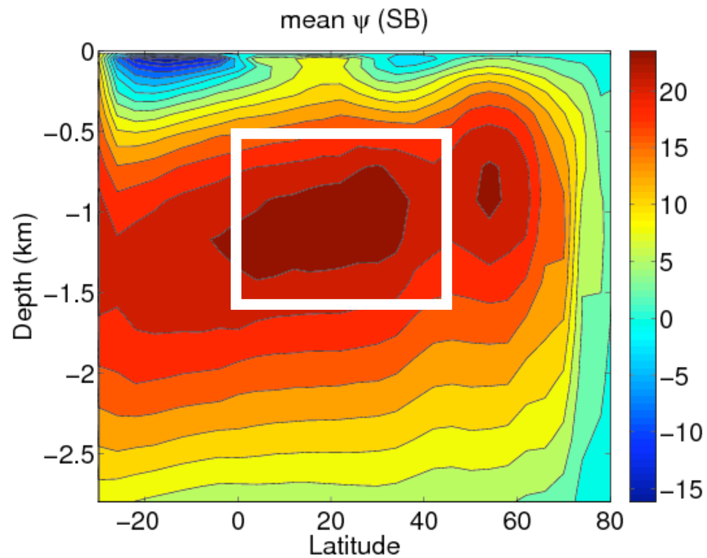
- Long term observations of MOC are scarce and models display a wide range of MOC decadal variability - poorly understood
- Goal is to develop a model-independent, diagnostic measure of MOC predictability
- Begin by exploring a model of intermediate complexity: aqua-planet configuration of the MITgcm

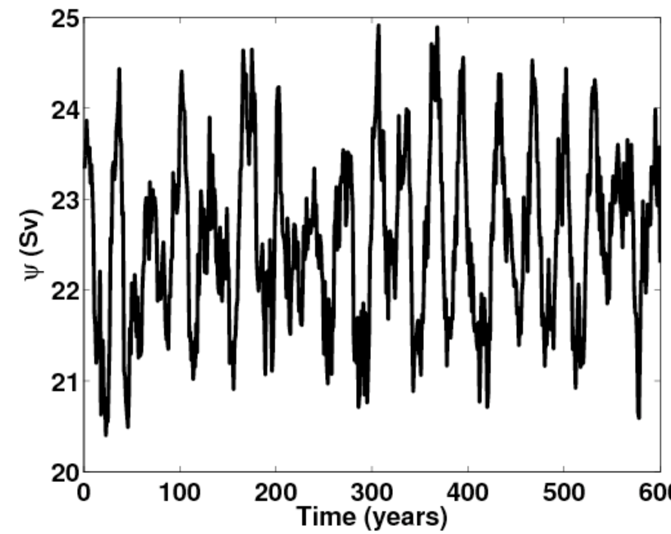
Double Drake (aqua-planet model)

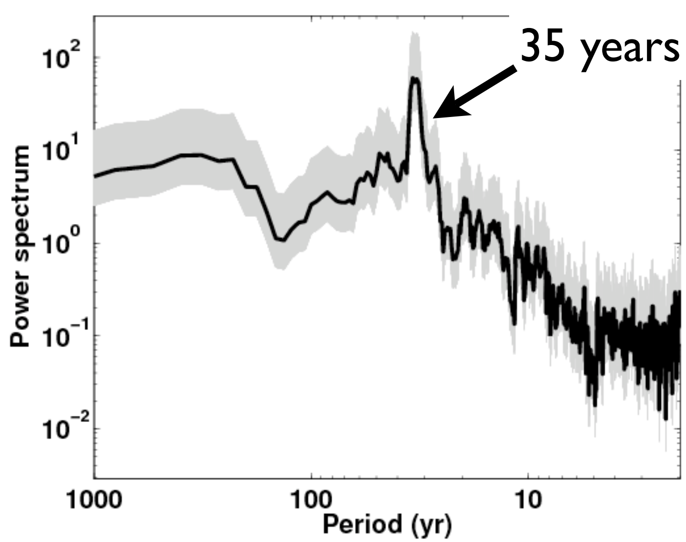
theta anomaly at 500m
when MOC is weak

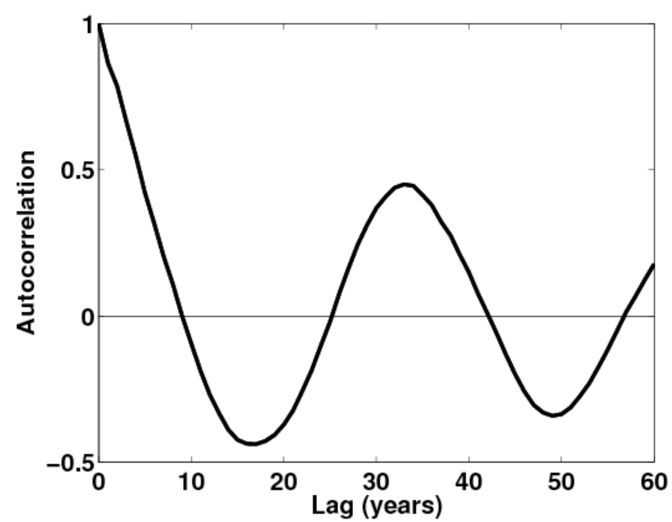
FLAT BOTTOMED (3km)



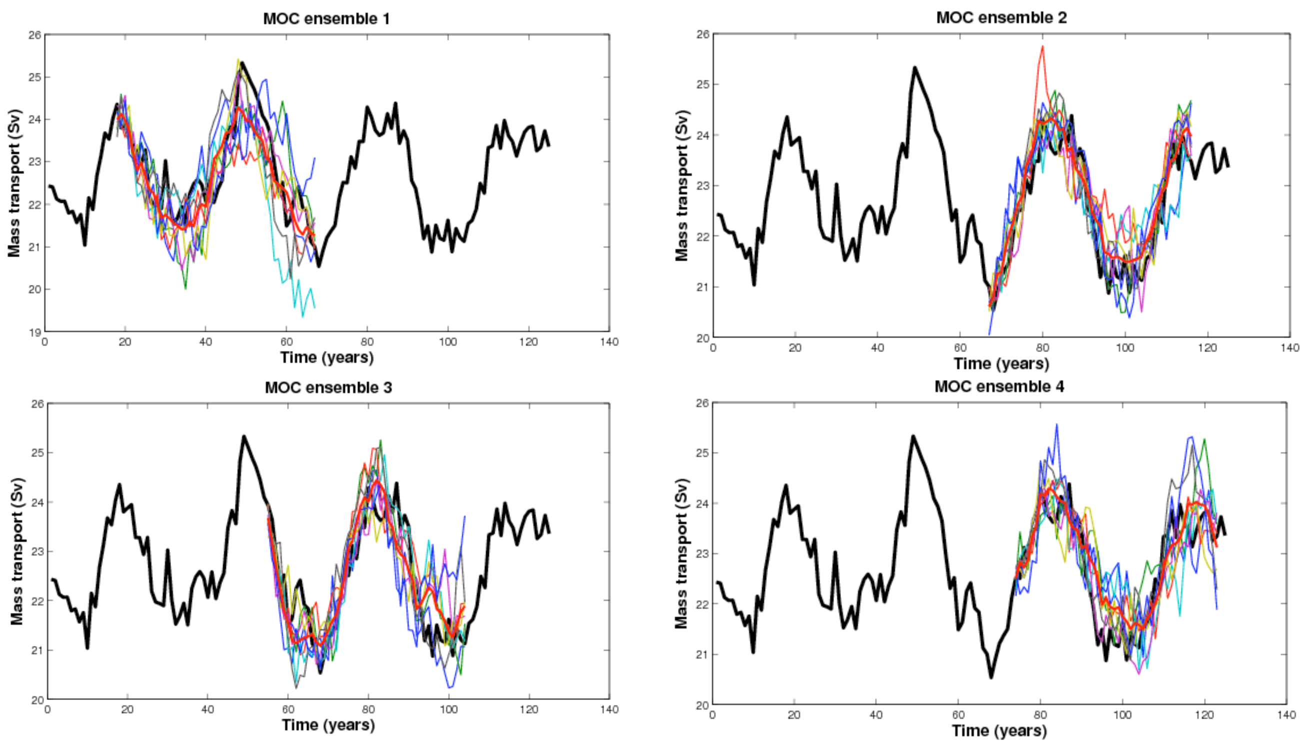








Double Drake: "Perfect" Ensembles

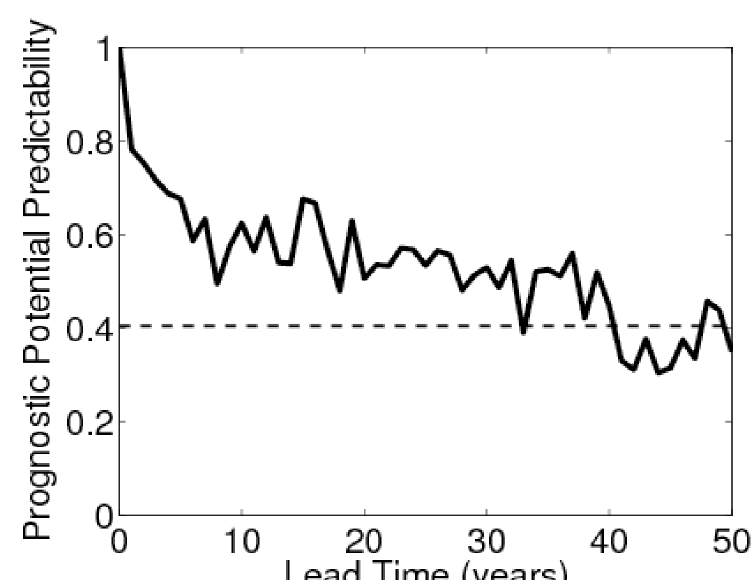


- "perfect" ocean IC's, with perturbed atmospheres
- all variability occurs on the western boundary
- predictable for at least one 35 year cycle

Prognostic Potential Predictability

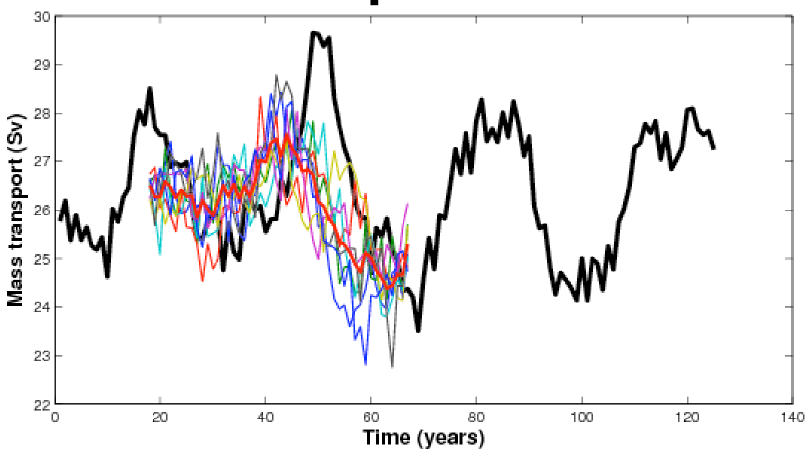
$$\mathrm{PPP}(t) = 1 - \frac{\frac{1}{N(M-1)} \sum_{j=1}^{N} \sum_{i=1}^{M} [X_{ij}(t) - \overline{X}_j(t)]^2}{\sigma^2}$$

$$\mathrm{PPP}(t) > 1 - \frac{1}{\mathrm{F}_{N(M-1),k-1}}$$

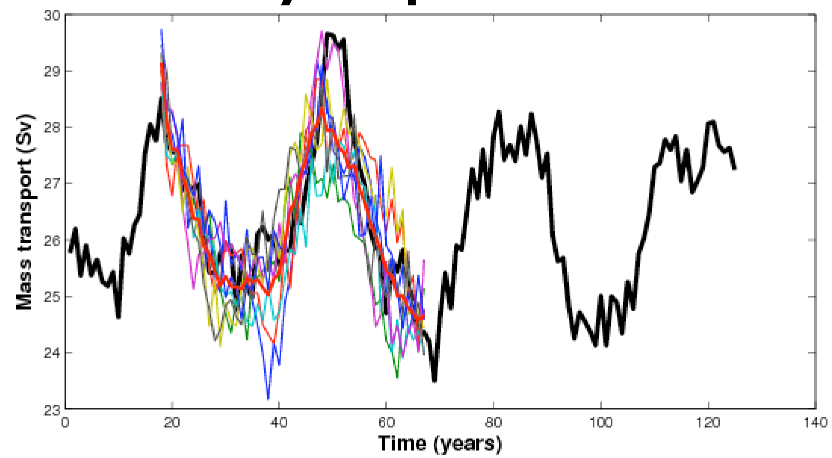


Double Drake: "Perfect" Ensembles ctd.

S and T perturbed



Only S perturbed

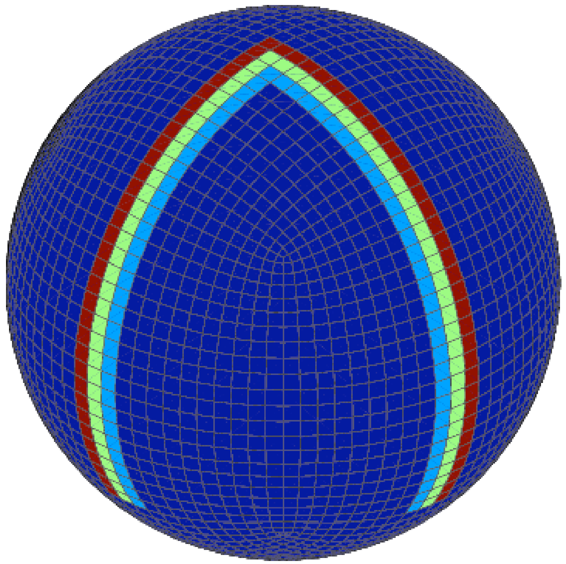


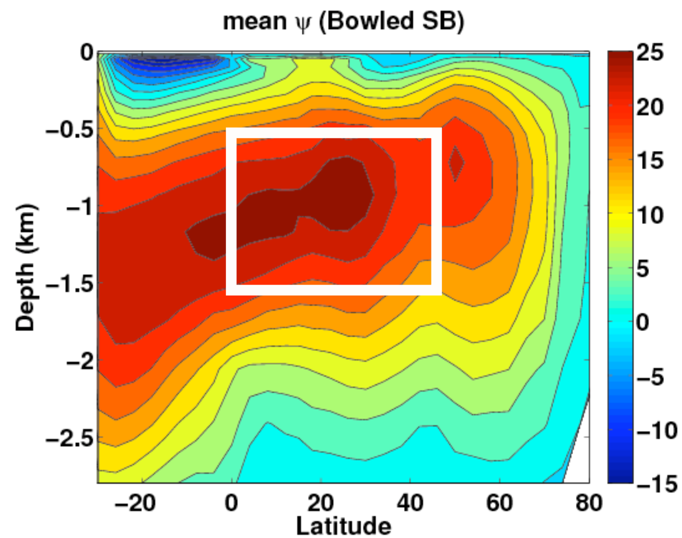
1. Temperature dominates MOC variability, salinity has little effect
2. Sampling frequency: IC's in the ocean can be averaged over a fraction of an oscillation period (~1/4 cycle) without losing much predictability.
3. Both the upper 1km and deep ocean are important for determining the phase of the MOC
4. Even though the temperature anomalies form on the eastern boundary, and all the MOC variability occurs on the western boundary, perturbing S/T on either boundary does not significantly alter the phase of the MOC

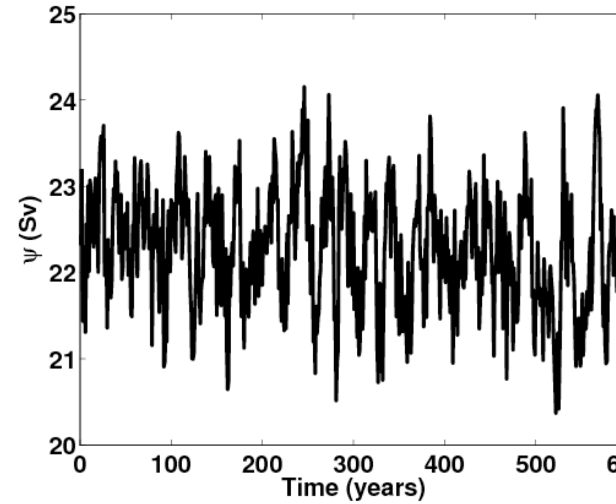
Bowled Double Drake

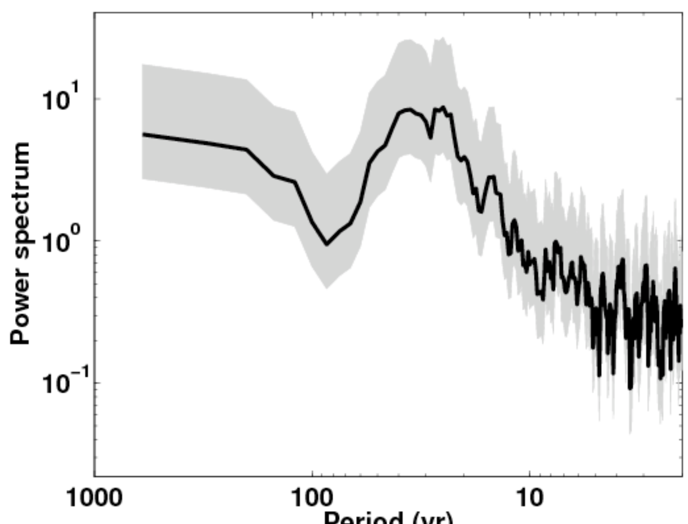
600 years of simulation after 1500 year spinup

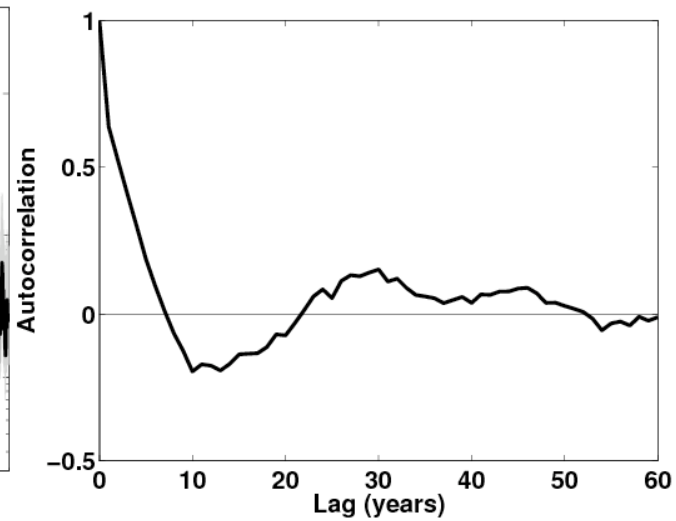
Bowl Bathymetry:
steps at 2.5km and 2km



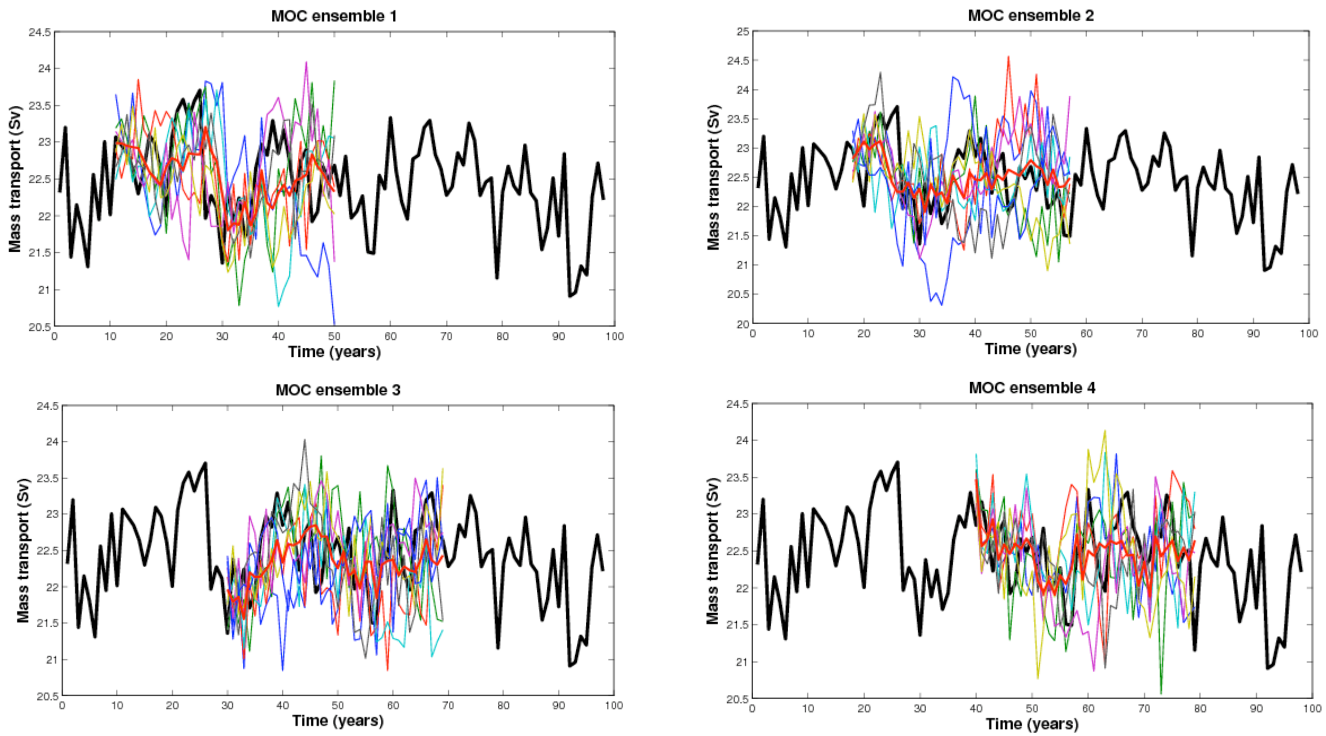






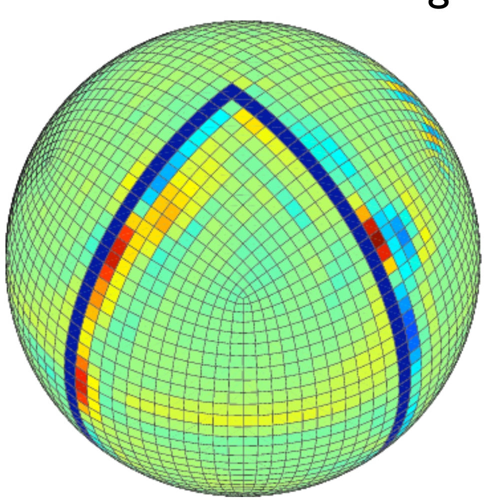


Bowled Double Drake: “Perfect” Ensembles

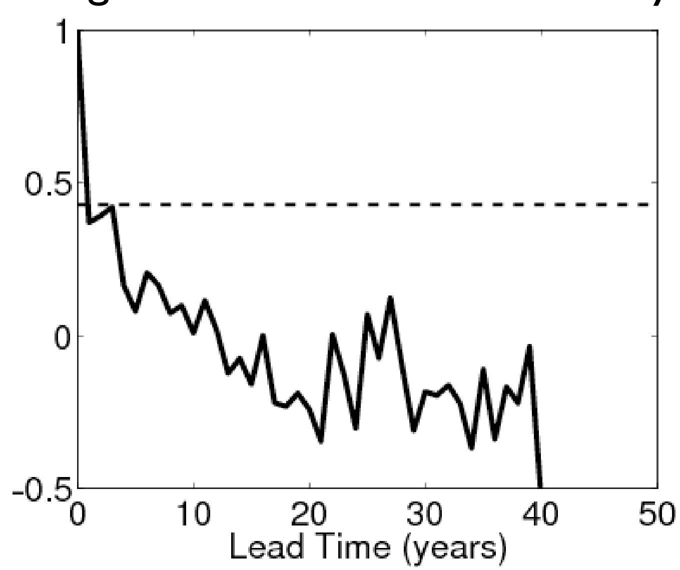


- ensembles track the MOC better when starting at a maximum or minimum (lower row)
- MOC variability still occurs on the western boundary
- high ensemble variance and low control variance implies low PPP.
- These are worst case ensembles since they assume no knowledge of the atmospheric state, which is likely the main forcing

surface meridional velocity when MOC is strong



Prognostic Potential Predictability

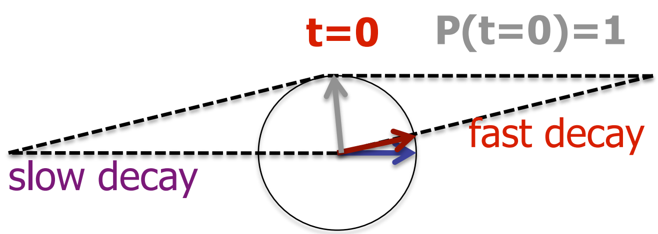


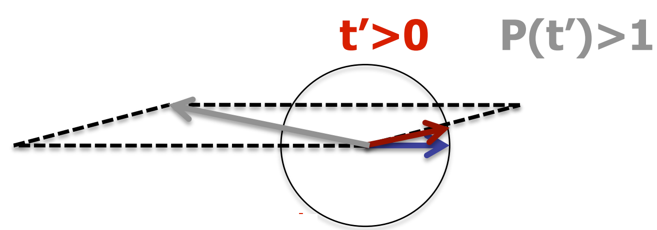
- A change from a flat to bowled bathymetry suppresses baroclinic instability near the eastern boundary, switching from an internally forced, highly predictable MOC to a stochastically forced, less predictable MOC.

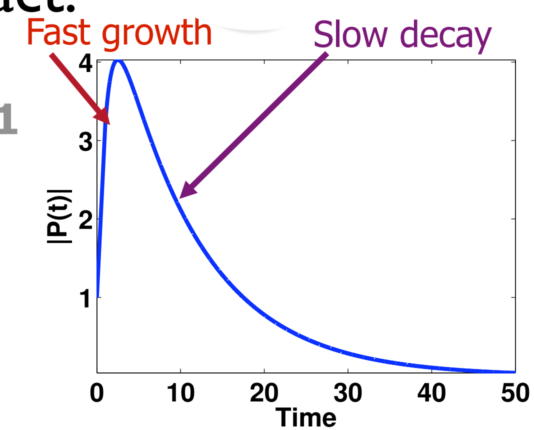
- How do non-normal dynamics change when we switch to bowled bathymetry?

Non-normal dynamics

- For a stable linear system $dP/dt = AP$, rapid, transient error amplification can occur (if the matrix A is non-normal) when decaying non-orthogonal eigenmodes interact.







Zanna (2008)

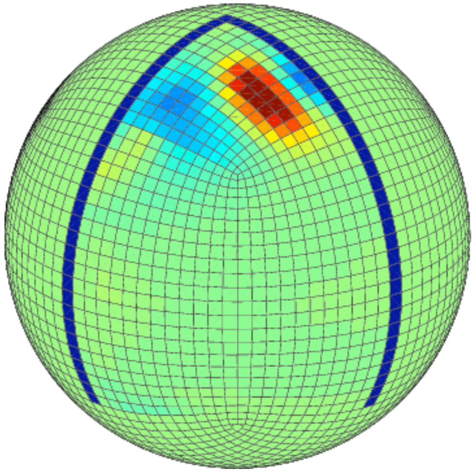
- Reduced space approach (Tziperman et al. 2008): assuming that the evolution of the principal components of the non-dimensionalized S and T fields is linear, a propagator matrix B can be obtained.

- Given the propagator matrix, the optimal initial conditions of the principal components are obtained from a generalized eigenvalue problem subject to either an energy norm or an overturning norm.

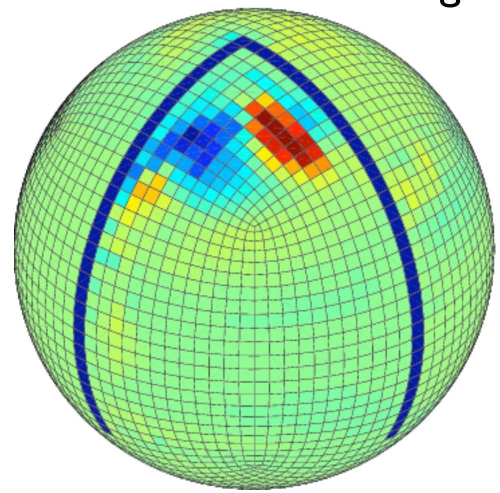
- The propagator matrix then predicts the rate of optimal error amplification.

Non-normal dynamics in the Double Drake

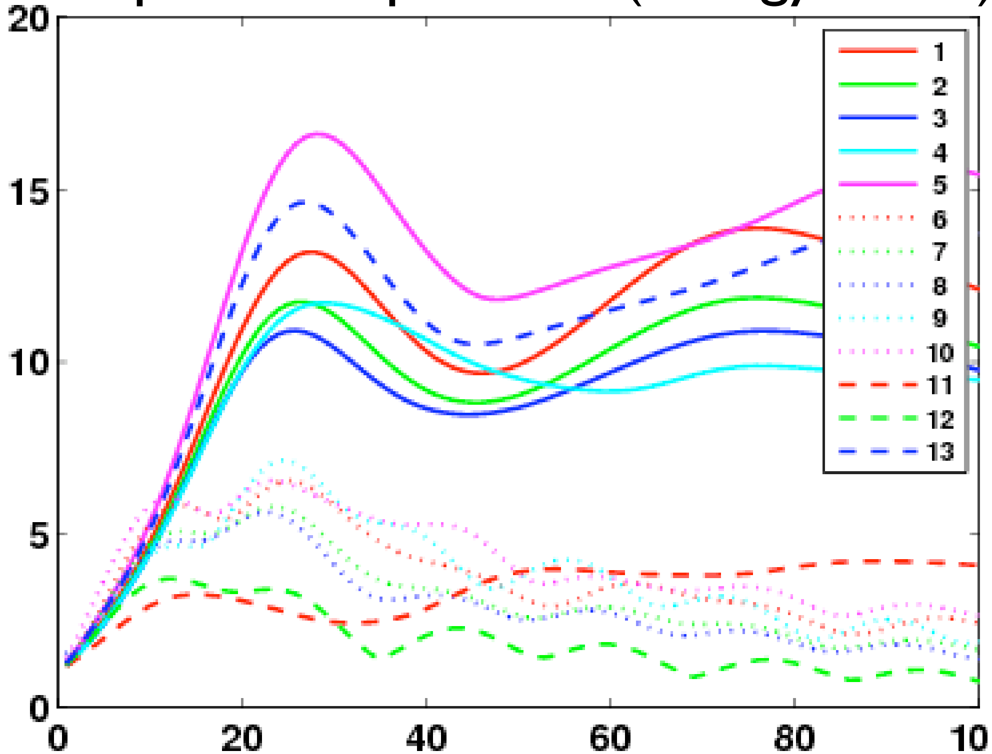
optimal IC (THC norm): theta at 500m



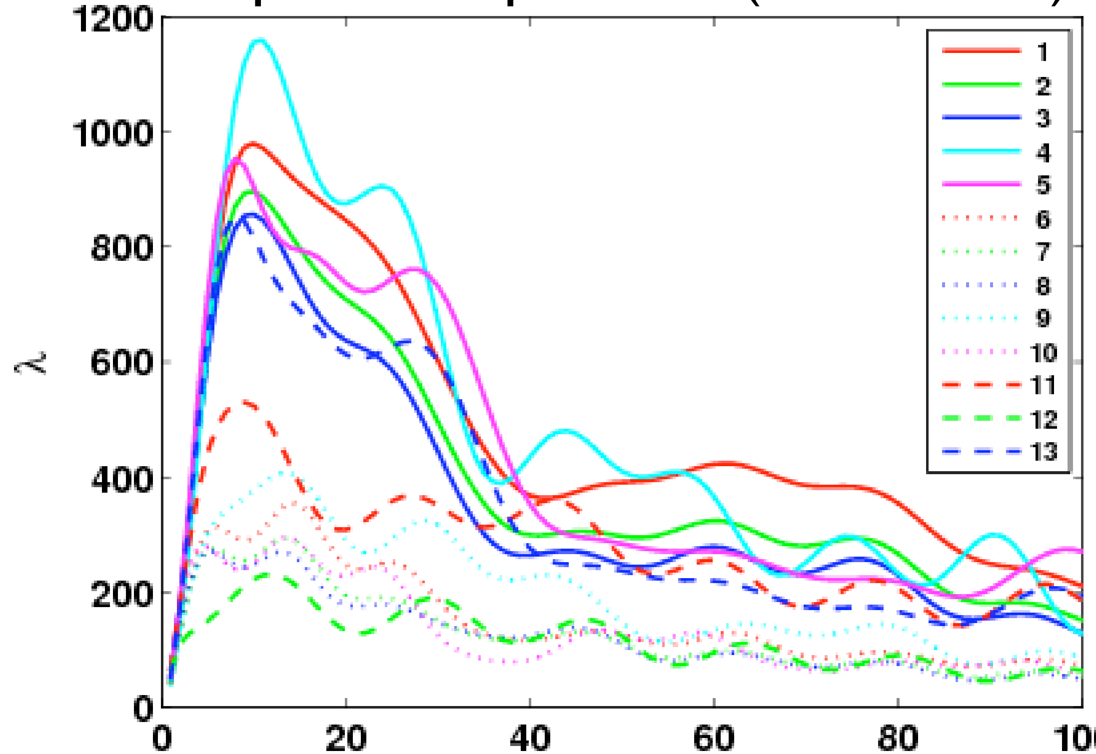
theta anomaly at 500m
when MOC is strong



Optimal amplication (energy norm)



Optimal amplication (THC norm)



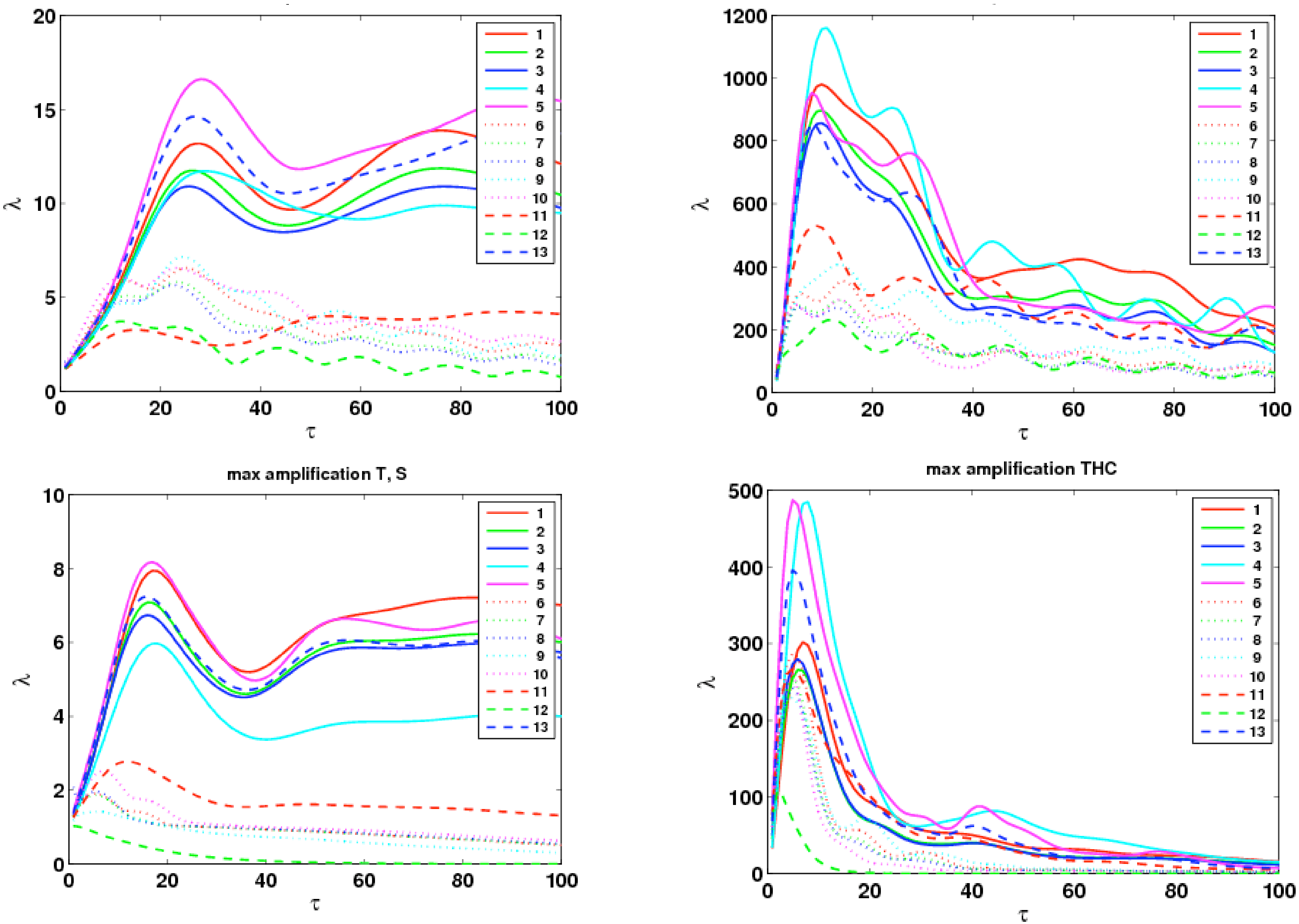
Double Drake versus Bowled Double Drake

Energy norm

THC norm

Double Drake

Bowled Double Drake

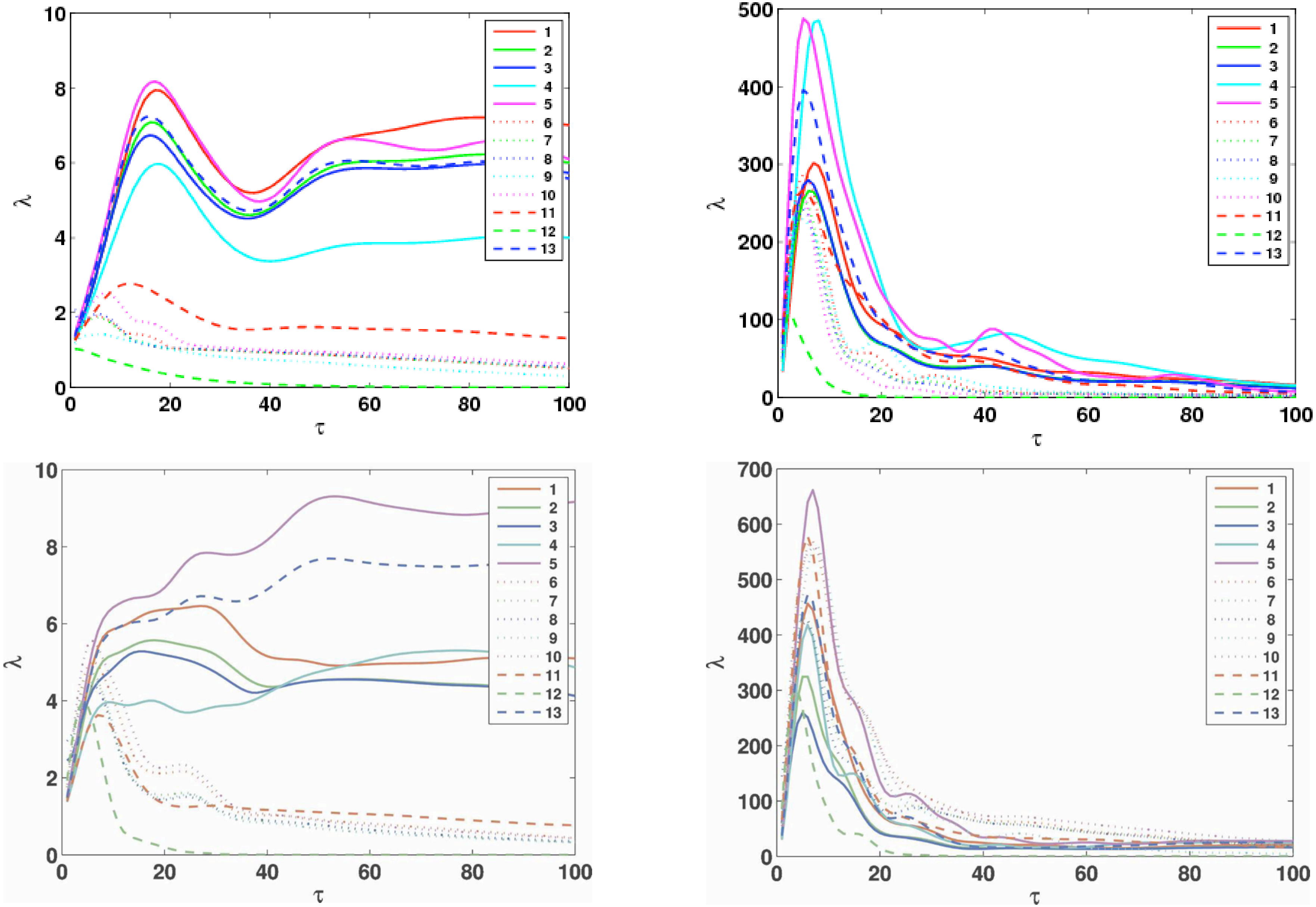


Comparison with CM2.1

Energy norm | THC norm

Bowled Double Drake

CM2.1



Tziperman et al. (2008)

Conclusions

- MOC in the Double Drake (DDR) is very predictable, due to internal instability which produces theta anomalies near eastern boundary (salinity not important)
- DDR with bowled bathymetry appears to be stochastically driven by the atmosphere, is harder to predict, though perhaps more realistic
- Optimal IC's in the DDR agree with composite high MOC theta
- Rates of optimal amplification are very similar between CM2.1 and DDR