Mechanisms of Atlantic Decadal Variability

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Motivation

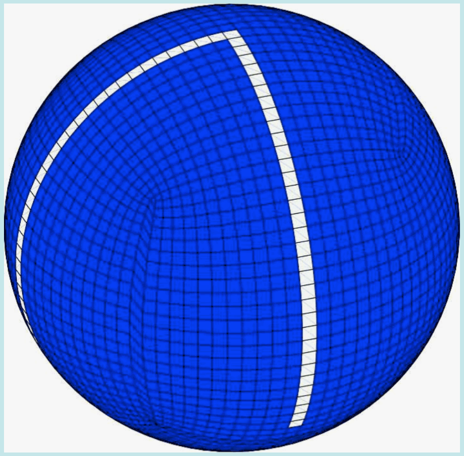
- Decadal SST and the AMOC variability has been observed in data and a variety of climate models ranging from idealized box models to realistic GCMs
- Underlying mechanisms of variability remain unclear and may be model dependent.

Our approach

Everything should be made as simple as possible, but not simpler.
--Albert Einstein

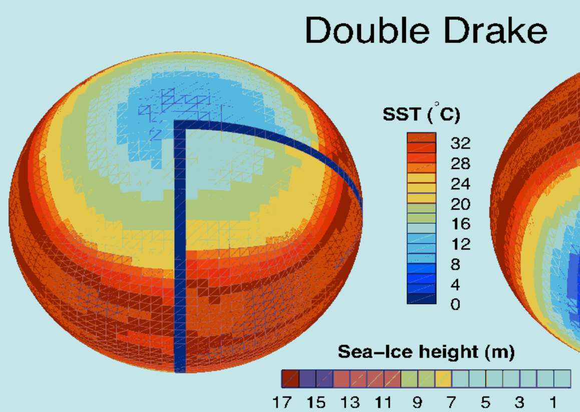
- The challenge: finding a model that is simple enough to be understood, but isn't so simple that is exhibits unrealistic behavior.
- Method: use a hierarchy of models

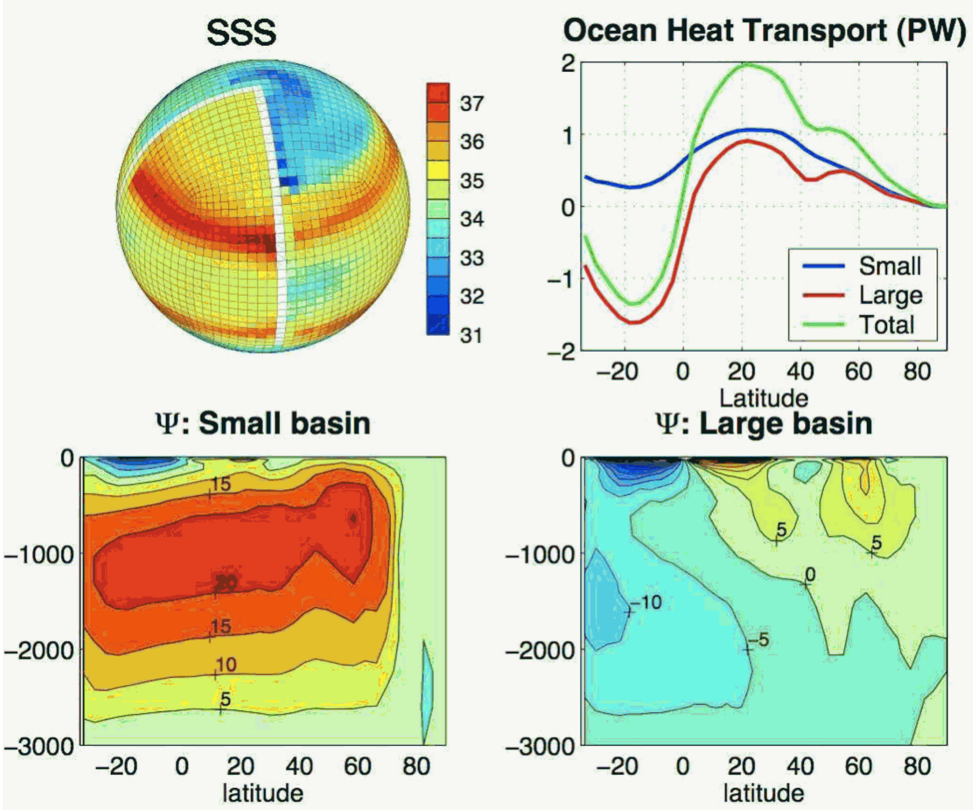
$\Rightarrow$



- Starting point = "Double Drake" model
    - Fully coupled MITgcm: realistic 3D atmospheric & ocean
    - Idealized geometry:
        - All water except 2 ridge extending from N. Pole to 34^{o}S
        - Flat bottomed ocean, depth of 3km

Mean State



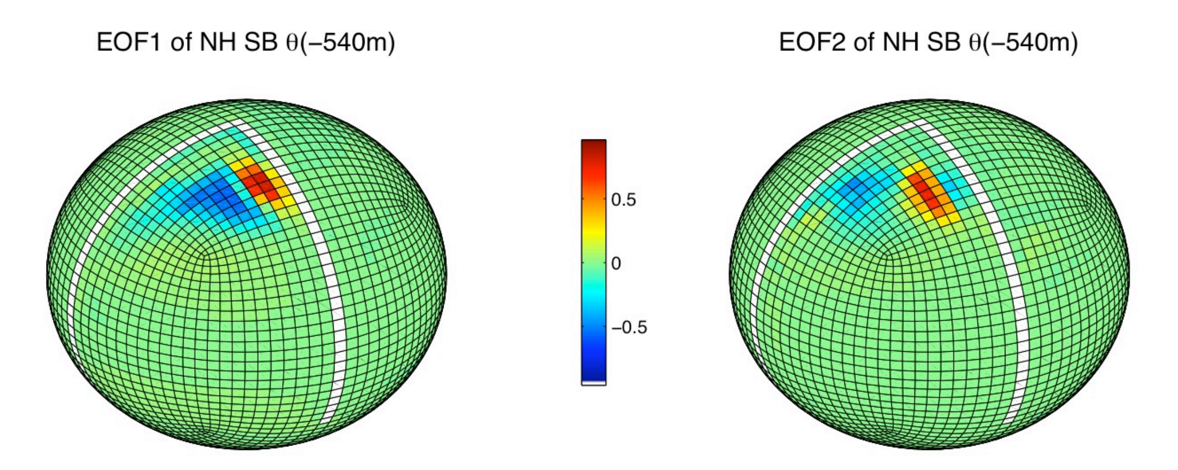


- Asymmetry betw hemispheres
  - S. Pole colder than N. Pole
  - Icecap over S. Pole
- Fresh large basin (LB) that is primarily wind-driven
- Salty small basin (SB) with meridional overturning circulation (MOC)
- Heat transport:
  - LB: Ekman and gyres, poleward both hemispheres
  - SB: Northward in both hemispheres due to contribution of MOC
- Small basin ~ Atlantic

D. Ferreira

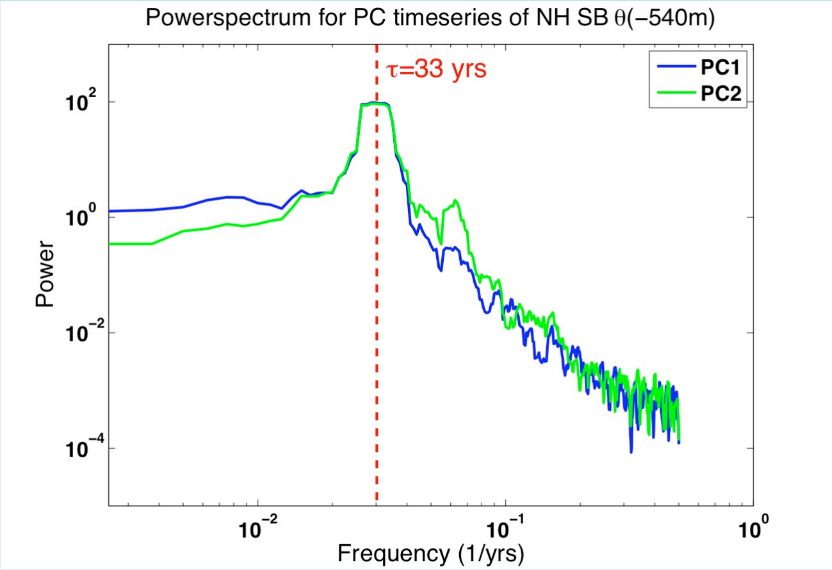
Thermal Variability on Decadal Timescales

EOF1 and EOF2 of Subsurface Temperature in NH SB:



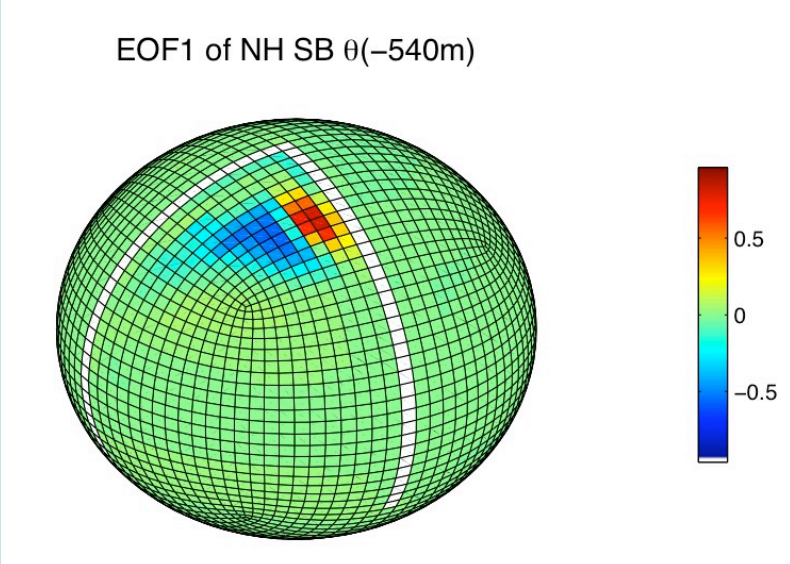
- First 2 EOFs explain 74% of variance
- Dipole at 60ºN: northern edge of subpolar gyre

Power Spectrum of PC timeseries:

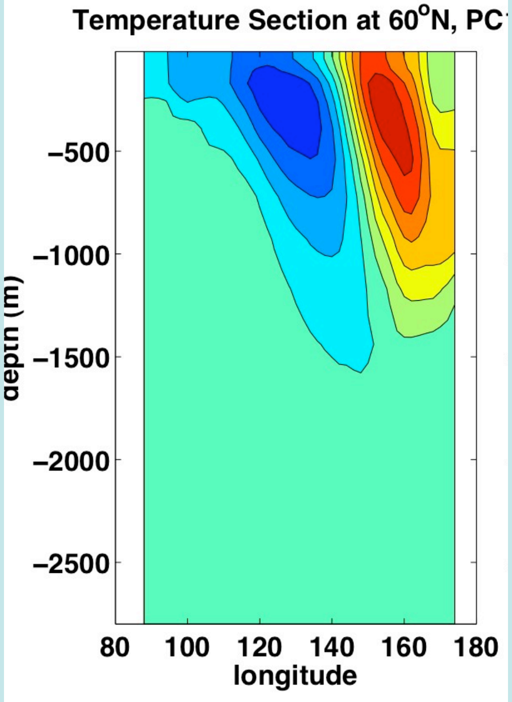


- PC1 and PC2 1/4 cycle out of phase ⇒ propagating mode
- Peak ~34 years

Origin of thermal anomalies



East-west section of temperature anomalies through 60^{o}N



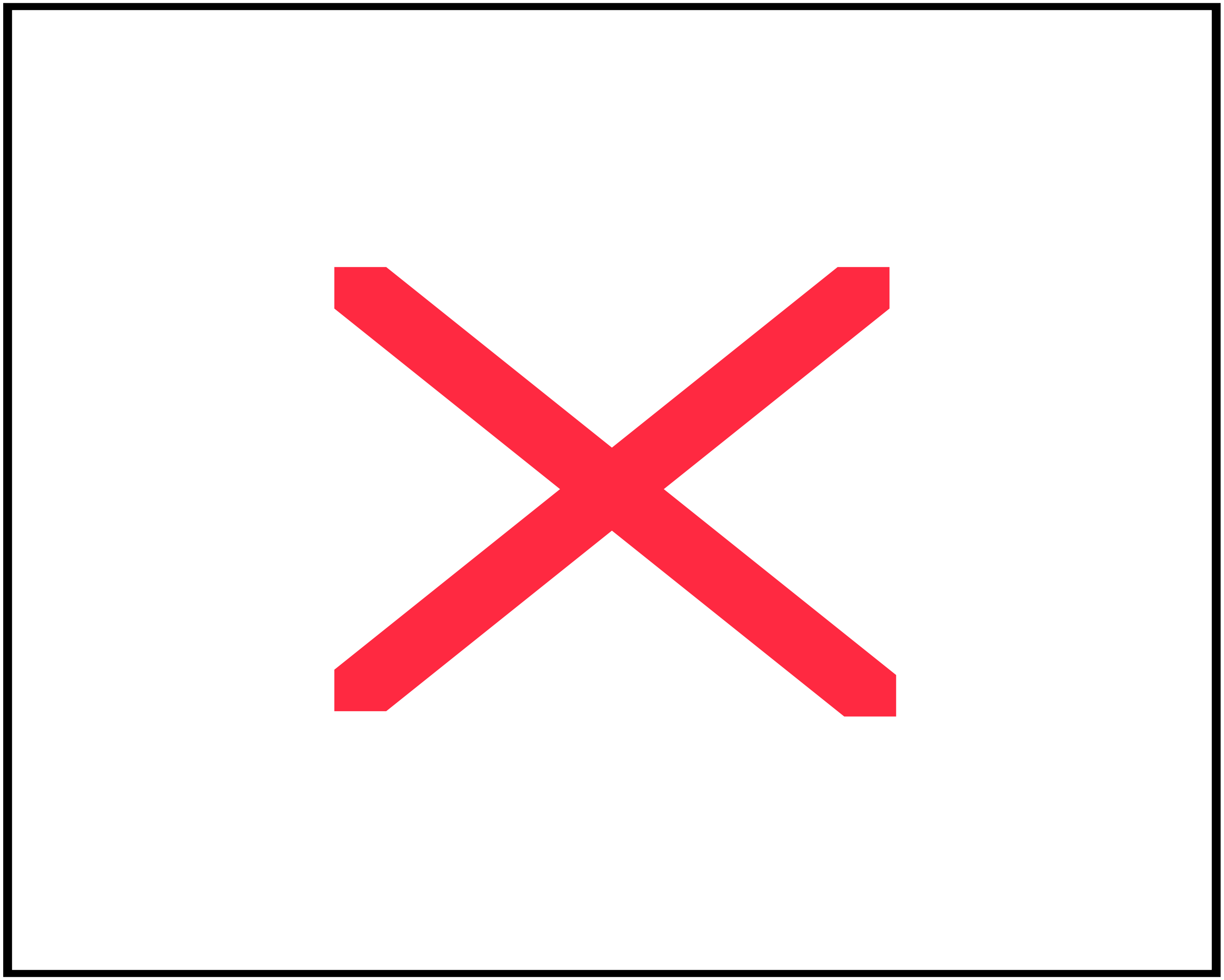
Movie of section of east-west section of temperature and associated air-sea heat fluxes at 60^{o}N.

Section of Temperature and HF at 60^{o}N

Origin of thermal anomalies

- Temperature anomalies originate near eastern boundary and propagate westwards as thermal Rossby waves.
  - Takes waves 34 years to cross basin.
  - Crossing time sets timescale of mode.
- SST anomalies damped by air-sea heat fluxes throughout their evolution.
- Temperature anomalies associated with compensating salinity anomalies, but density anomalies are dominated by temperature.

Variability of the MOC



Variability of the MOC

Inter-hemispheric MOC

- Variability driven by temperature on WB.
- $\theta' < 0$ on WB $\Rightarrow$ positive MOC anomaly at 60^{o}N.
- MOC anomaly propagates southward, taking 8 years to reach maximum extent.

- Timescale of oscillation is set by time for waves to cross basin.

Source of Energy for Oscillations

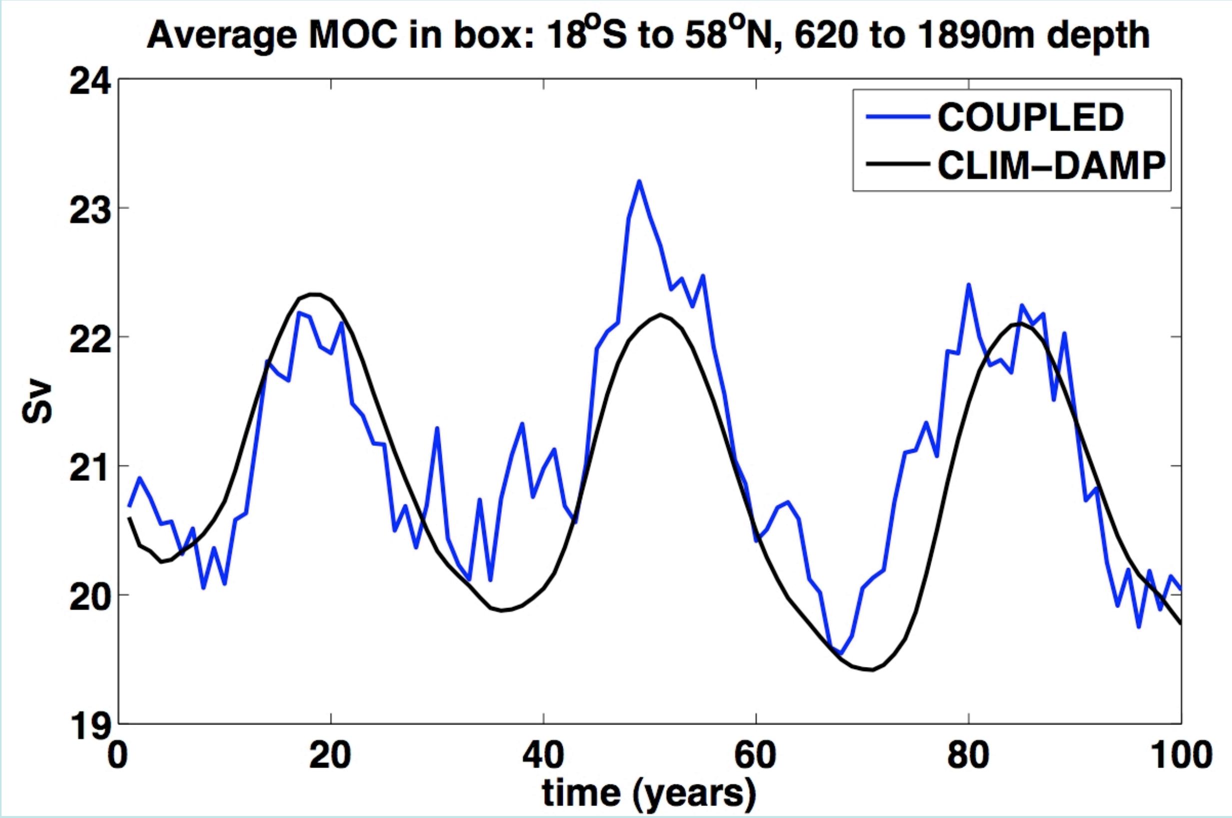
Is atmospheric variability needed to excite waves?

Conducted ocean-only experiments:

COUPLED

CLIM-DAMP:

- Initialize w/state from coupled model.
- Force with climatological heat, freshwater, and momentum fluxes + damping of SST on 71 day timescale



- Variability in coupled model is well reproduced by a running ocean-only model w/ climatological fluxes & damping of SST anomalies.
- Decadal mode is a self-sustained ocean-only mode.

Model Hierachy (so far)

Toy models

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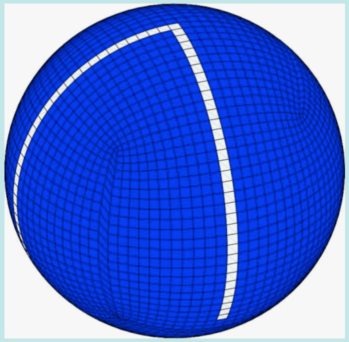

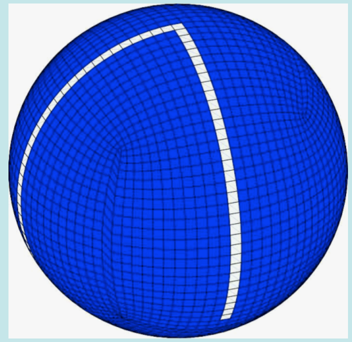

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Ocean-Only Double Drake w/ clim forcing

Coupled Double Drake

Simple

Complex

- But are these self-sustained oscillations robust?
- Or is the model too simple, exhibiting special behavior due to its simplicity?
- Try adding coastal bathymetry.

Model Hierachy (so far)

Toy models

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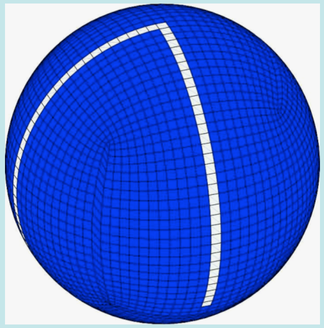
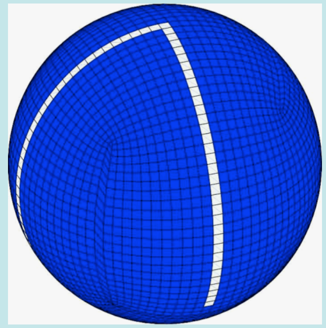
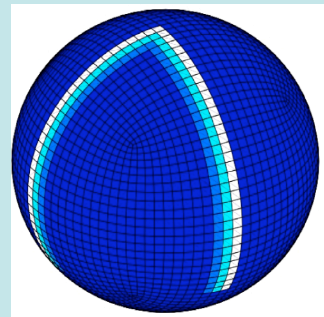


Ocean-Only Double Drake w/ clim forcing



Coupled Double Drake



Double Drake w/ bowl bathymetry

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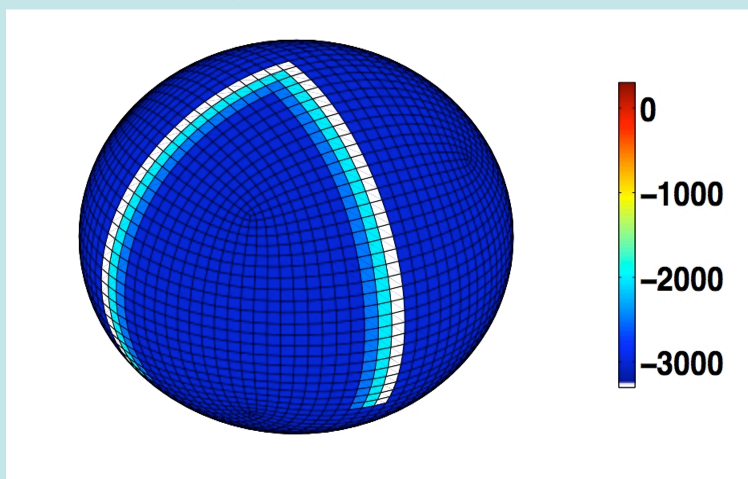
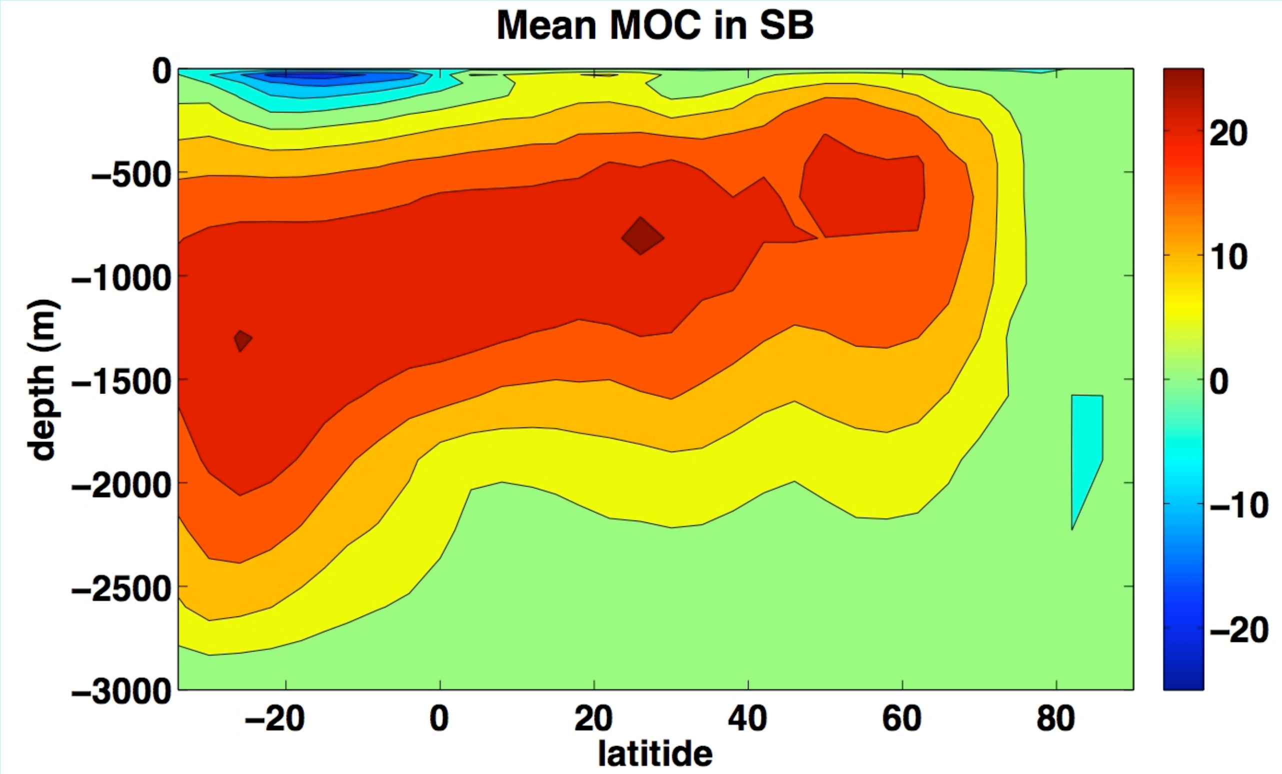
Simple

Complex

Depth of Ocean



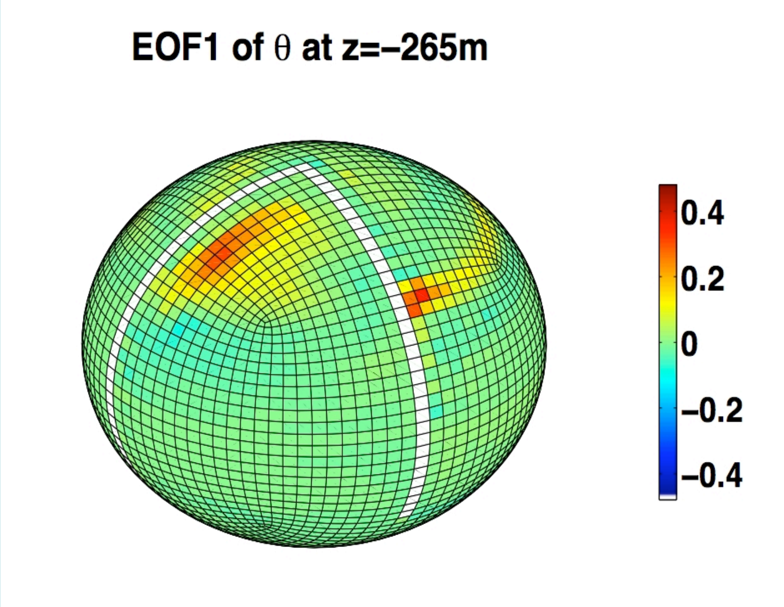
Double Drake with Bowl Bathymetry

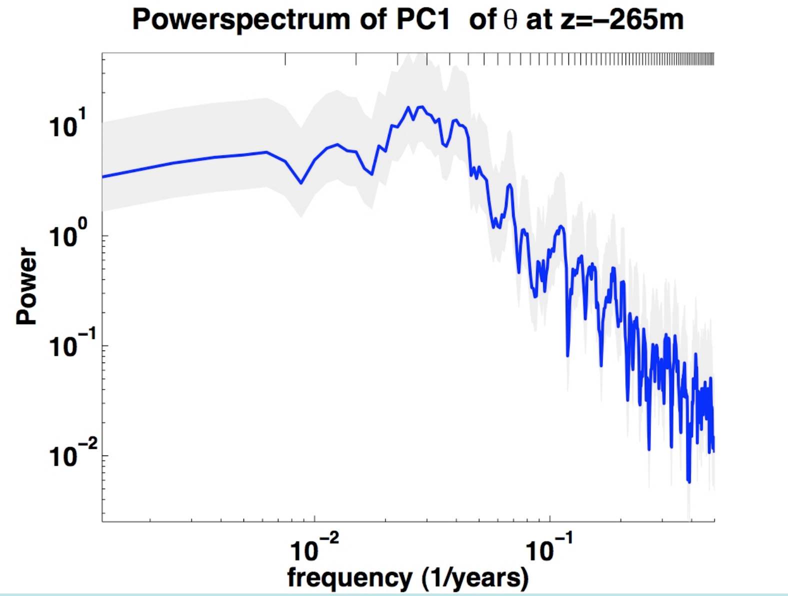


- Ocean-only experiments show that no thermal, MOC variability when model forced with climatological forcing.
- MOC, temperature oscillations are not self-sustained in presence of bathymetry!
- Run coupled model with bathymetry.

Variability in Coupled Model with Bathymetry

- Temperature variability
  - Max temperature anomalies concentrated on western boundary.
  - Still a broad peak at a timescale of 34 years!
  - Thermal Rossby waves still appear to be setting timescale of variability.
- MOC variability:
  - Much of variability associated w/ wind variability: wobbling of atmospheric jets.
  - Still observe MOC anomalies associated with temperature anomalies on the western boundary.





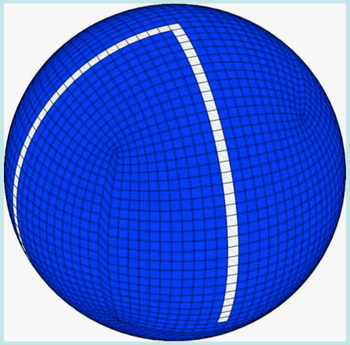
Conclusions

- Working to develop a hierarchy of models that are useful for understanding the mechanisms of decadal climate variability.
- Robust conclusions (so far)
    - Timescale of temperature and MOC variability set by time it takes for thermal Rossby wave to cross the basin.
    - The MOC responds to temperature anomalies on the western boundary.

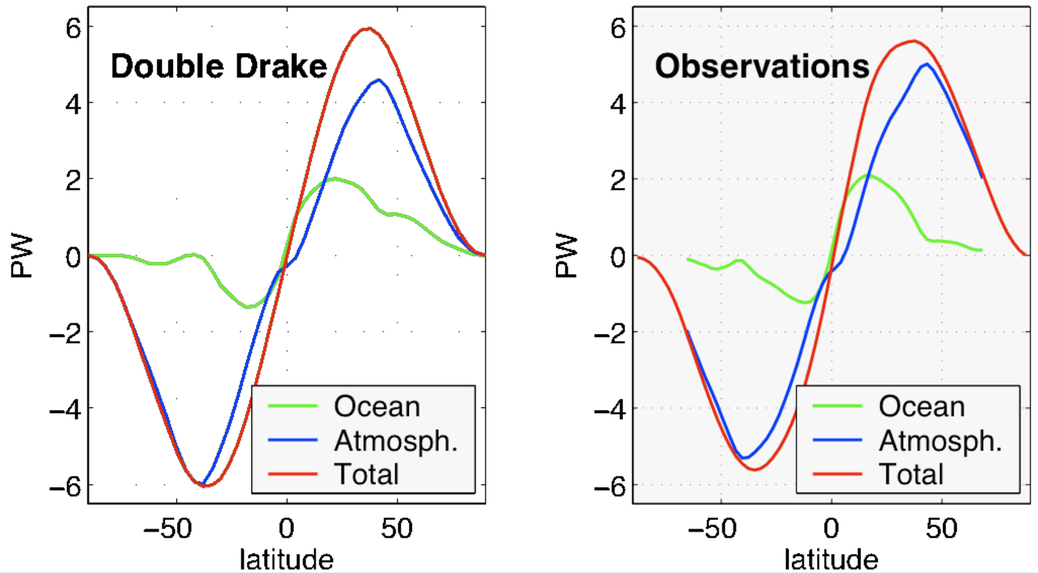
Extra slides---

MITgcm: Double Drake Model

Double Drake



Earth



Why “Double Drake”?

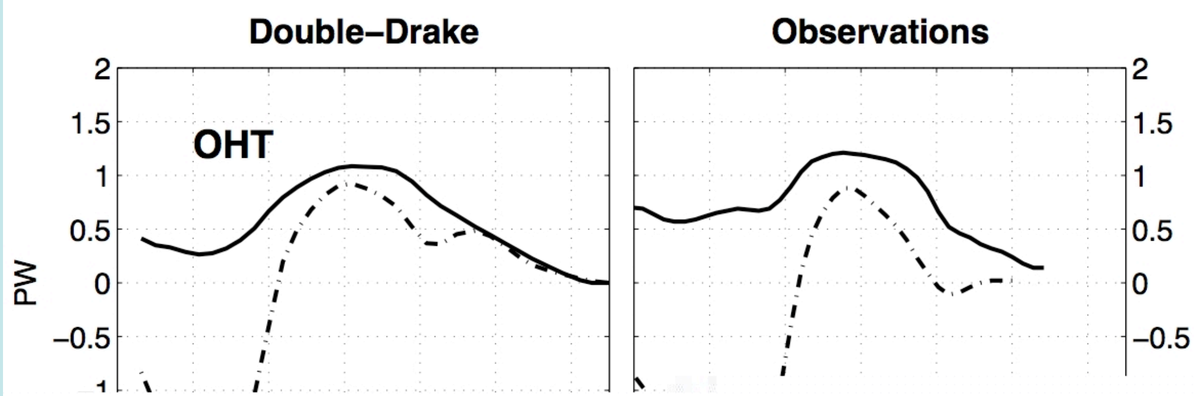
- Simple
- Resembles earth in many ways

Run in simple geometry

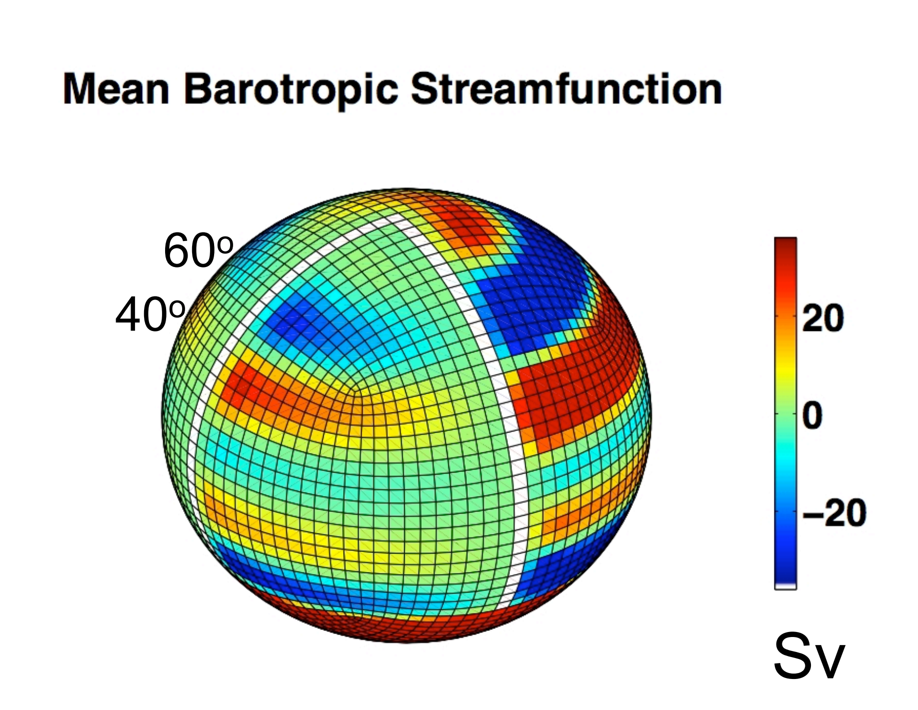
- All water except 2 ridges run from N. Pole to 34°S
- 3 ocean basins
  - Small basin “Atlantic”
  - Large basin “Pacific”
  - Zonally unblocked “Southern Ocean”

- A&O: cubed sphere grid at C24
- Resolution: 3.7° latitude
- 5 level atmosphere, primitive equations (SPEEDY)
- Flat bottomed ocean, depth=3 km, 15 levels
- Parameterized eddies (G&M)
- Convective adjustment
- Integrated from rest to quasi-equilibrium
- 800 year timeseries

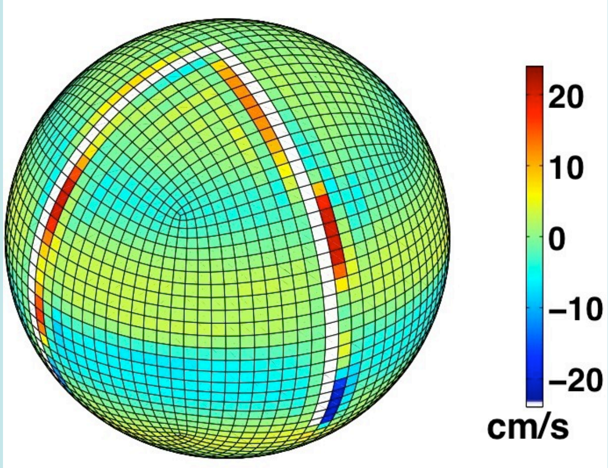
Comparison to Observations



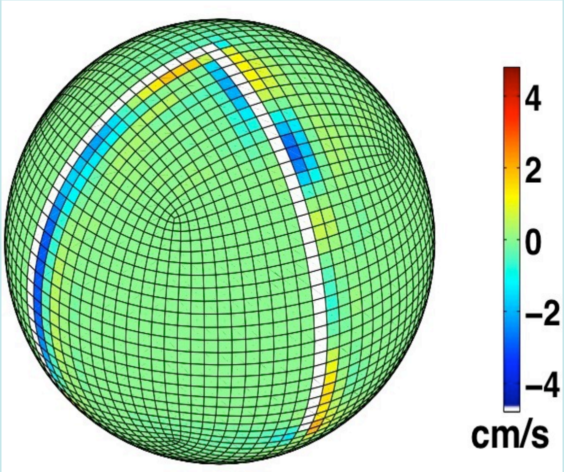
Mean Currents



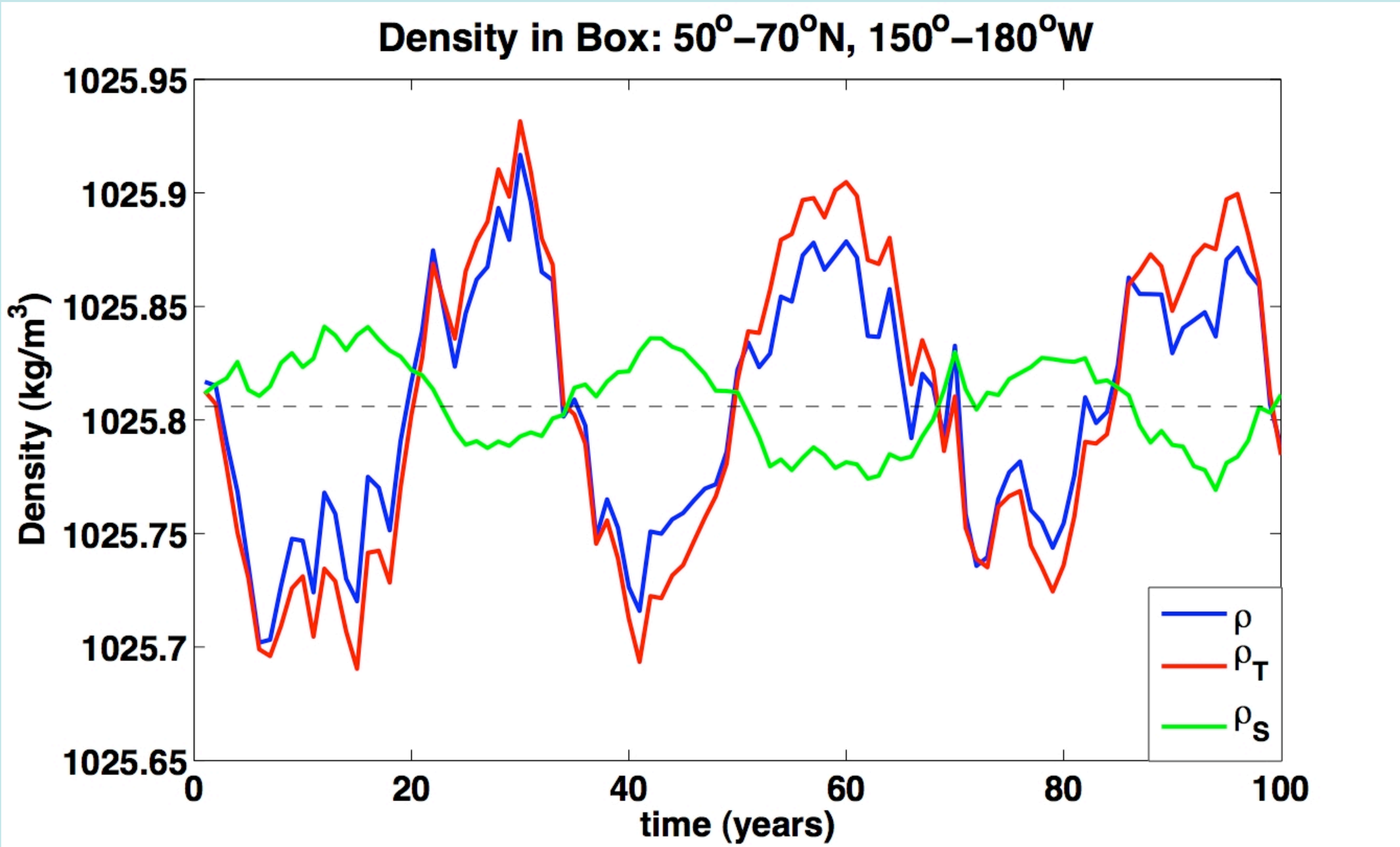
Meridional Surface currents



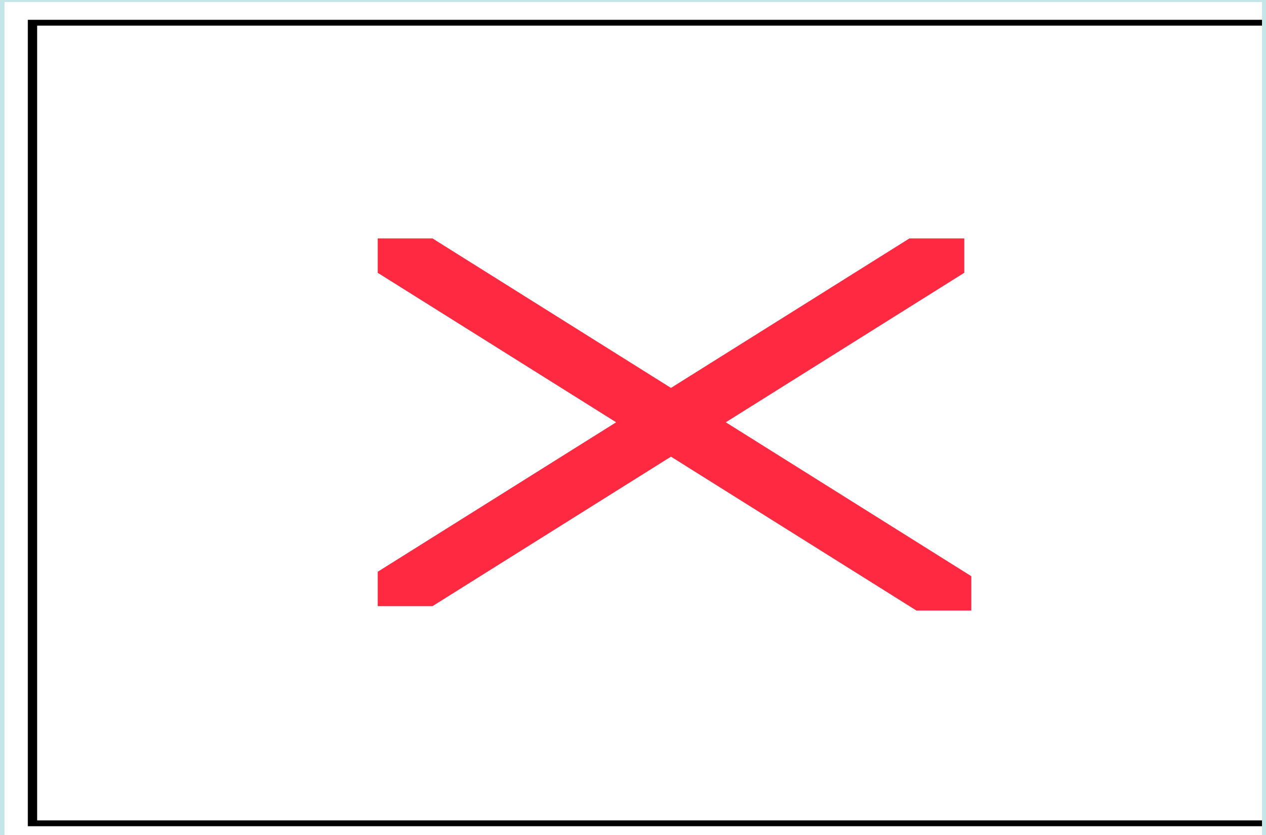
Meridional Deep currents



Density Anomalies: Dominated by Temperature



Thermal Rossby Waves



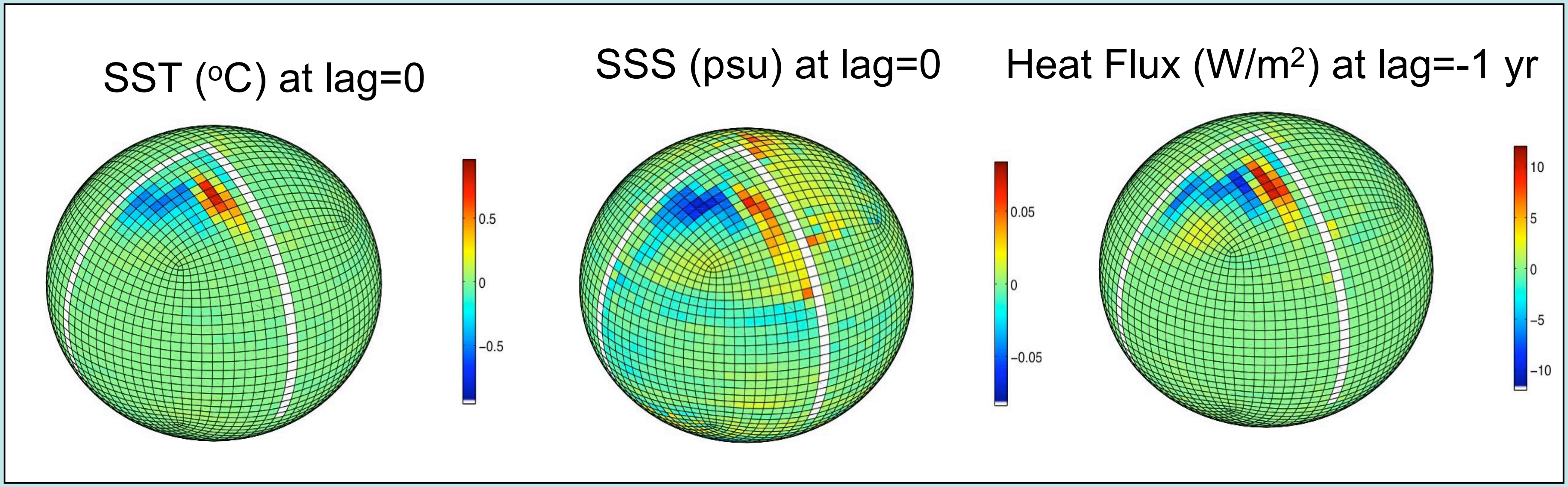
- Phase velocity of anomalies: c= -0.6 cm/s
  - Observed phase velocity matches simplified prediction of thermal waves living on mean meridional temperature gradient.
  - Takes anomalies ~34 years to for anomalies to cross basin

SST Variability on Decadal Timescales

What surface anomalies are associated with subsurface variability?

Project data field of interest onto PC timeseries

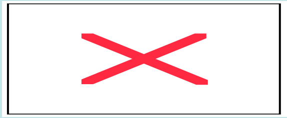
⇒ Spatial pattern of variability



- SST anomalies damped by air-sea heat fluxes throughout evolution
- SST anomalies associated with salinity anomalies (but density anomalies are dominated by temperature)
- Ocean circulation plays a role in creating anomalies!

(show movie)

Variability of the MOC

- MOC has 2 regions of variability
  - **Locally forced** convective region (60^{o}N to N. Pole)
    - Meridional velocity anomalies are local thermal wind response to zonal thermal anomalies.
  - **Remotely forced** inter-hemispheric region (34^{o}S to 60^{o}N)
    - Variability driven by temperature on WB.
    - $\theta'<0$ on WB $\Rightarrow$ positive MOC anomaly at 60^{o}N.
    - MOC anomaly propagates southward, taking 8 years to reach maximum extent: 
- Variability in 2 regions is linked by thermal Rossby waves.
- Timescale of oscillation is set by time for waves to cross basin.

Source of Energy for Oscillations

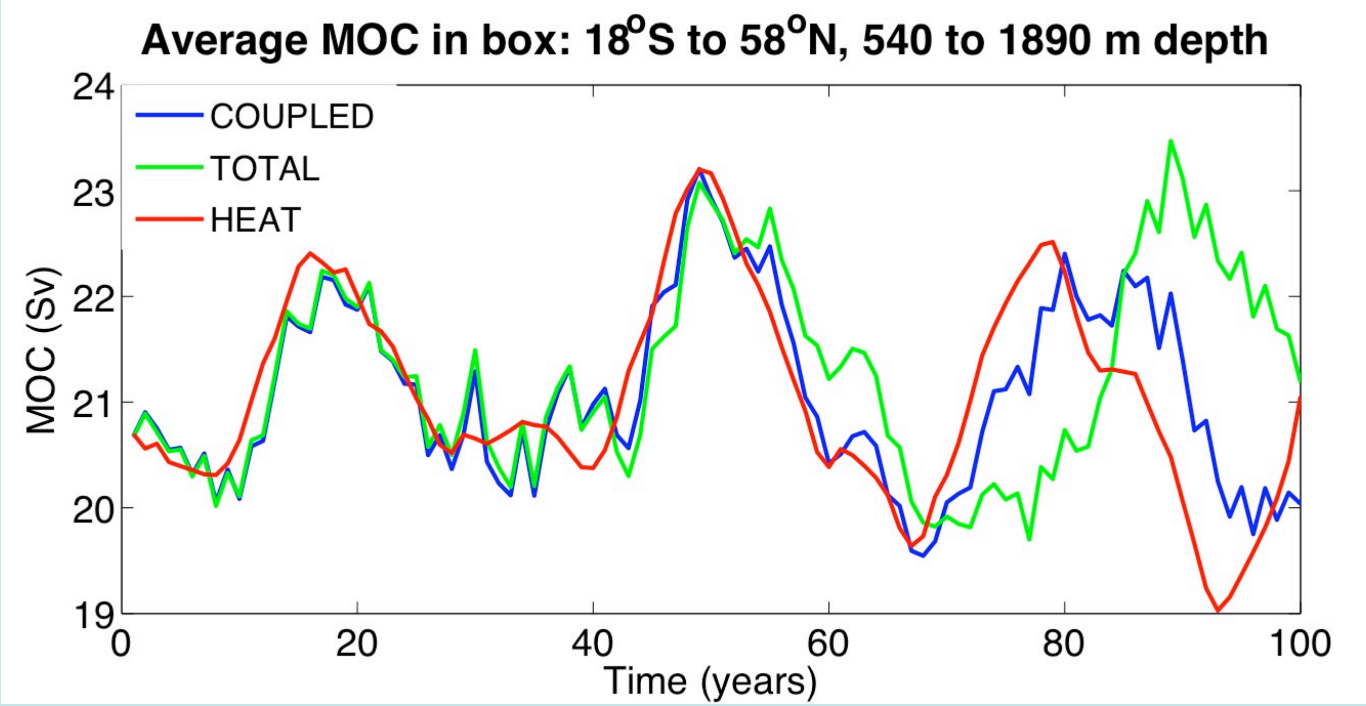
Ocean-only model experiments:

- Initialize with state from coupled model.
- Force ocean model with 5 day timeseries of heat (HF), freshwater (FW), and momentum fluxes (MF).

COUPLED

TOTAL:
force with HF, FW, and MF from coupled model

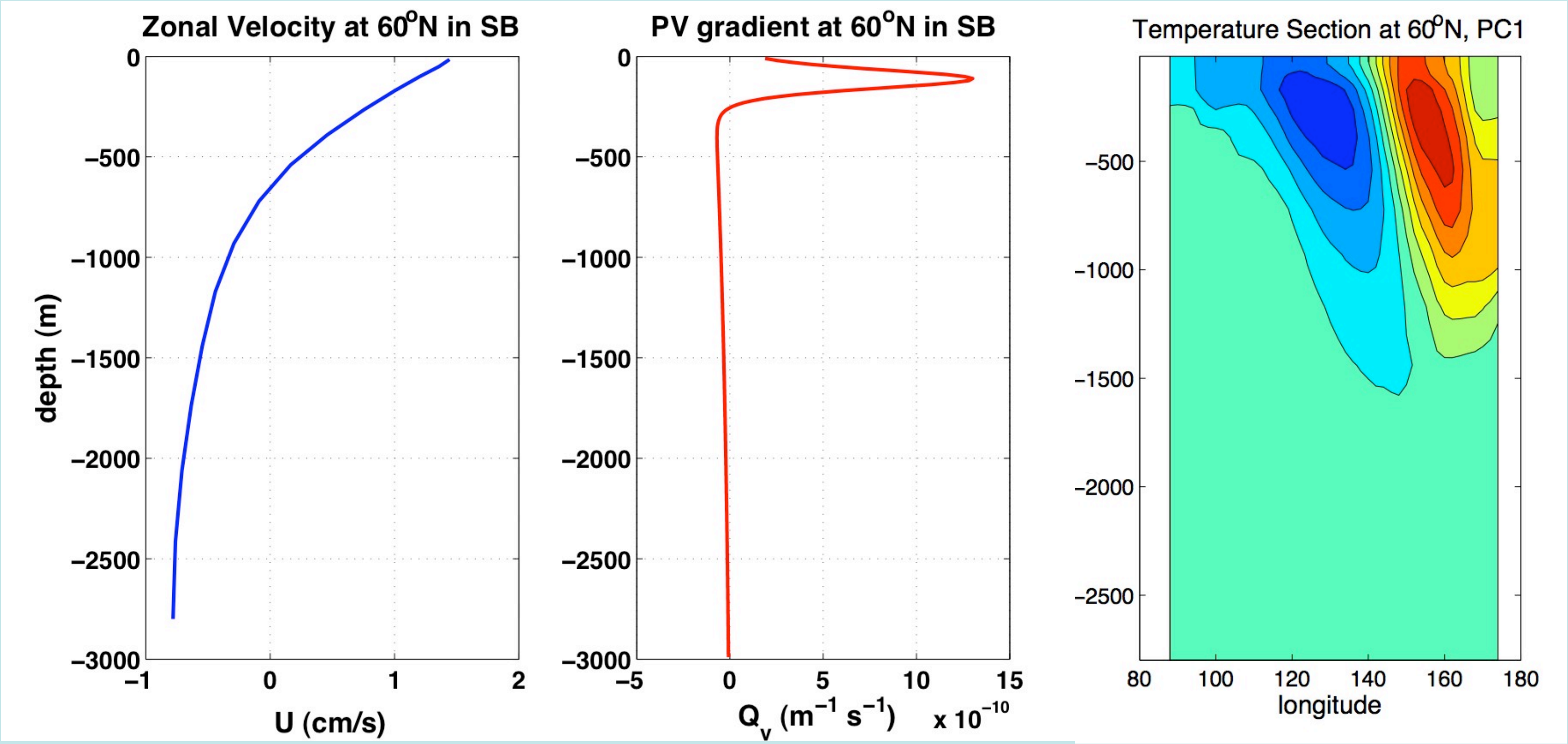
HEAT :
force with HF and climatological FW and MF



Specifying heat fluxes to ocean-only model is sufficient to reproduce decadal variability observed in the coupled model.

Source of Energy for Oscillations

Must be source of energy to enable mode to grow against damping.
Could source of energy be APE, released via baroclinic instability?



- PV gradient reverses sign w/ depth.
- Waves tilt against mean shear.

$\Rightarrow$ Waves can release APE via baroclinic instability & grow

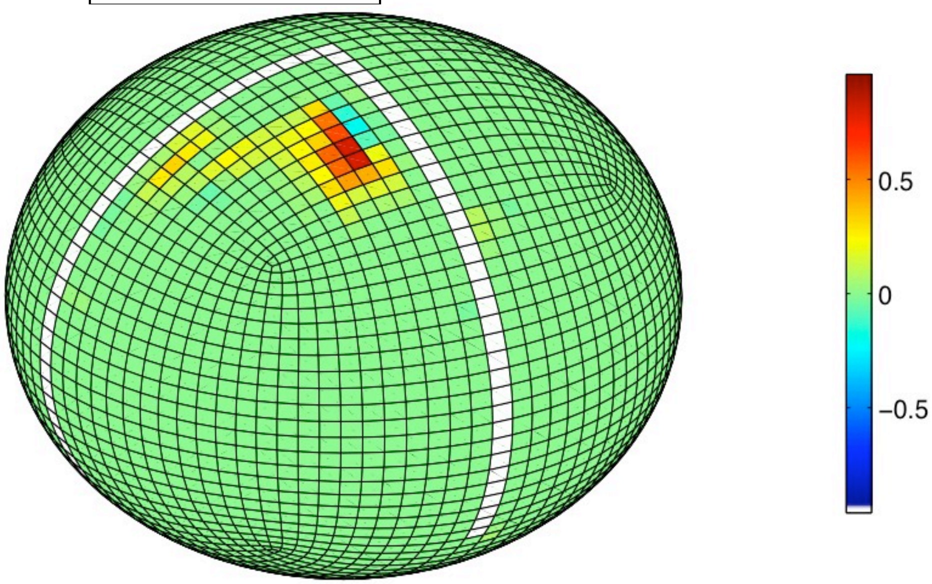
Creation of Temperature Variance by Eddies

Time mean linearized temperature variance equation:

$$\frac{1}{2}\frac{\partial \overline{T'^2}}{\partial t} = -\frac{1}{2}\bar{\mathbf{u}} \cdot \nabla \overline{T'^2} - \overline{\mathbf{u}'T'} \cdot \nabla \bar{T} + \overline{D'T'} + \overline{F_T'T'},$$

Time tendency	transport of variance by mean flow	creation/ transport of variance by eddies/waves.	destruction of variance by mixing/ convection	destruction of variance by air-sea heat fluxes

(°C/yr) in top 320 m



- Domain average:

$\Rightarrow$ eddies/waves create variance

- Analysis can't tell me where variance is created.
- Locally: - $\Rightarrow$
    - Local creation of variance

  OR

    - Advection of variance to location by waves