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On mechanisms of interdecadal climate variability: Coupled and uncoupled integrations with a simplified climate model

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Mechanisms of Atlantic Interdecadal Variability in a Simplified Climate Model

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A simplified Coupled Ocean-Atmosphere-SeaIce model

The Ocean

- MOM4. Atlantic-like configuration with Drake Passage and sea-ice model. [0-60W; 75S-75N]; $2^\circ \times 2^\circ$; 24 uneven vertical levels.

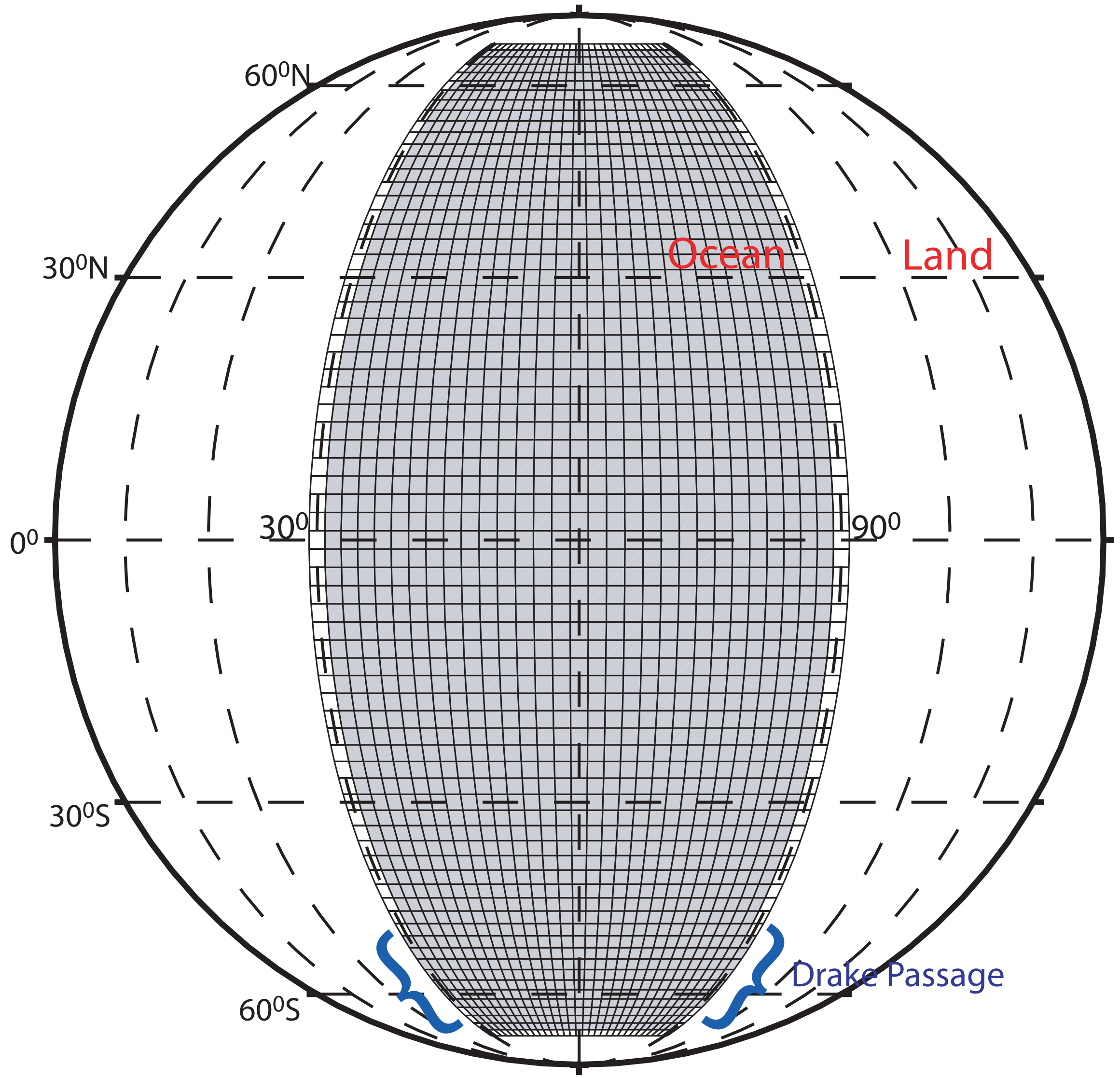
The Atmosphere

- GFDL AM2.0 PE B-Grid model. 120°sector with simplified physics
  1. Simple radiation scheme (Grey: water vapour prognostic and radiative fluxes $f(T)$ only).
  2. Simple Monin-Obukhov boundary layer scheme.
  3. Simple Convective-adjustment scheme (Betts-Miller: T and q relaxed to post-convective reference profile).
  4. No clouds; no seasonal cycle.

The Land

- LM2.0. Single bucket land. Constant C_p, α and water availability. Simple river map redistributes precipitation back into the ocean.

The Grid



1. Atmospheric sector: $3^\circ \times 3.75^\circ$; L7.
2. Ocean Basin: $2^\circ \times 2^\circ$; L24.

Experiments

Coupled Experiments

- Fully dynamical ocean model.
  1. With and without periodic channel (ACC)
  2. With different values of vertical diffusivity κ_v
  3. With different geometry
  4. Scaling Experiments (Δsol, Ω, q, ...)

Uncoupled Experiments

- Atmos-only
  1. Slab mixed-layer ocean model (Swamp).
  2. Flux-adjusted slab mixed layer ocean model (Q-flux).
  3. Fixed-SSTs (taken from dynamical ocean).
- Ocean-only
  1. Suite of forced runs with different coupled fluxes (MBC,FBC).

Goals of this Study

→ What are the characteristics of the Low Frequency Variability (LFV) in the COUPLED SYSTEM?

1. Who is driving whom and at what time scales?
2. Can the Ocean force the Atmosphere?
3. Can the system be coupled under certain conditions?

→ What sets the *VARIABILITY* of the Heat Transport in the Ocean & Atmosphere?

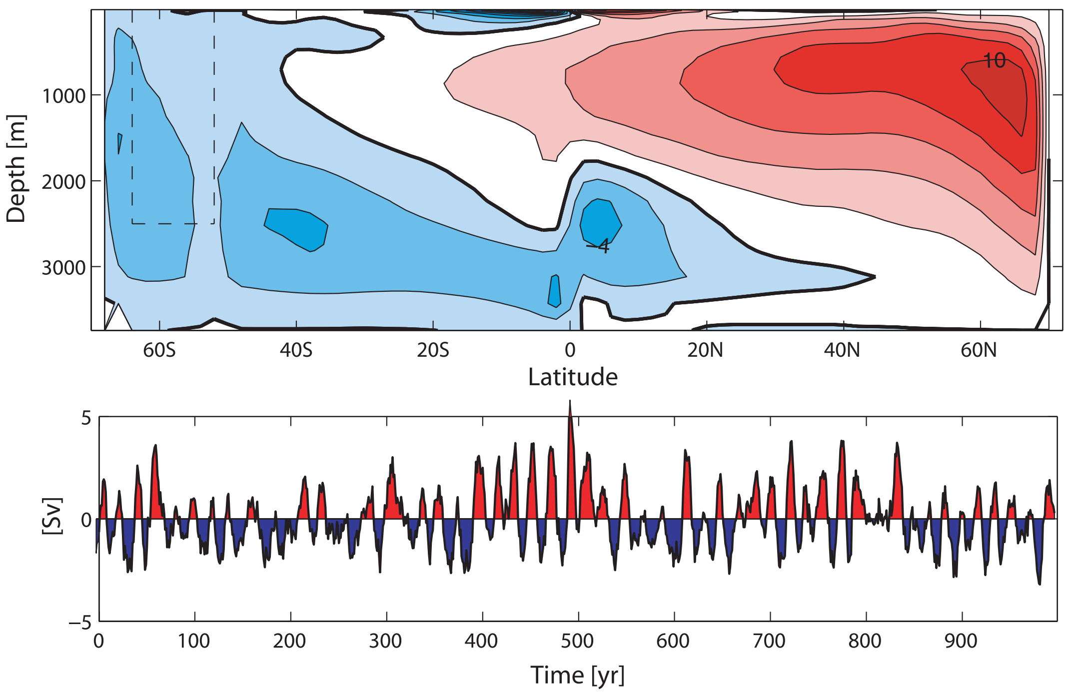
1. Can we detect compensation (Bjerknes effect)?
2. How is this involved in the LFV of the system?

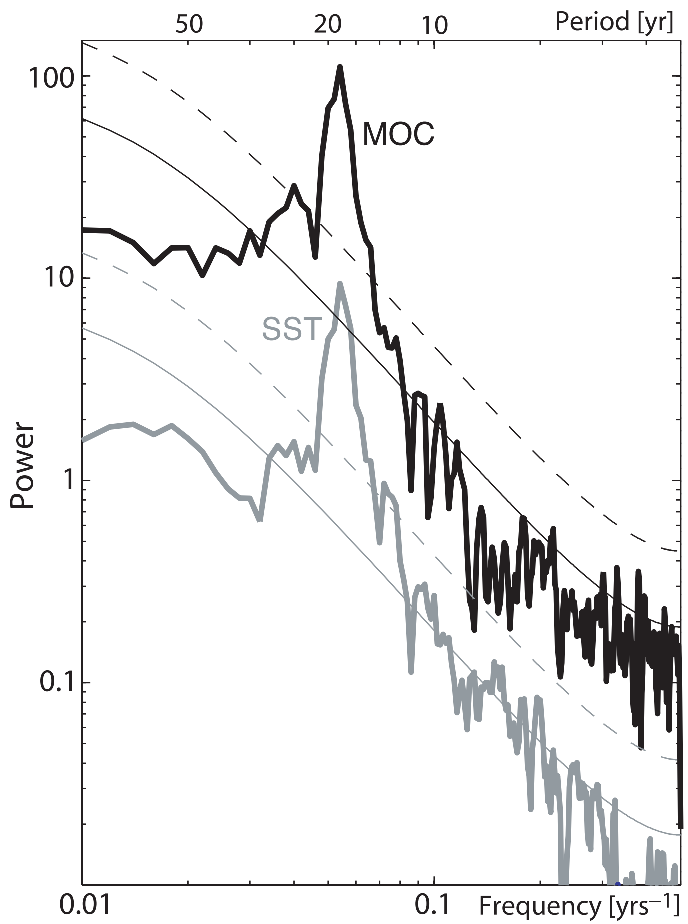
⇒ Can we relate the following results to state-of-the-art CGCMs?

General Mechanisms of Ocean-Atmosphere Interaction

1. The null-hypothesis (e.g., Frankignoul&Hasselman, 1977):
   The atmosphere varies stochastically (white noise), the passive ocean integrates this variability providing red noise spectra.
2. Stochastic forcing of a damped oscillator (e.g., Griffies&Tziperman,1995; Delworth&Greatbatch,2000):
   The ocean is excited by the atmospheric variability.
3. Coupled modes of variability (e.g., Latif&Barnet, 1994):
   Non-trivial feedbacks between atmosphere and ocean.
4. Intrinsic oceanic variability (e.g., Greatbatch&Zhang,1995):
   The ocean variability expresses itself spontaneously.

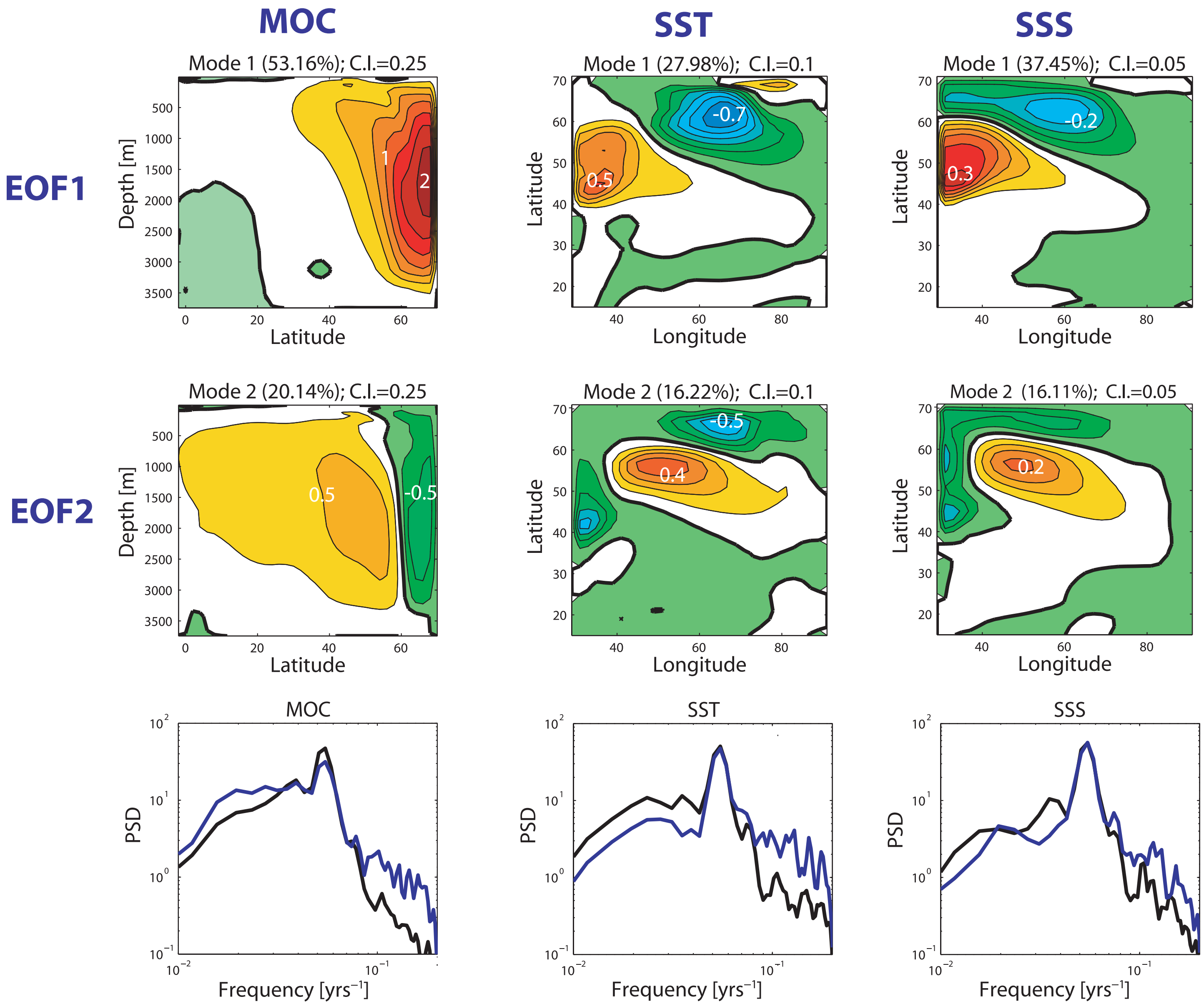
MOC Variability in Control case



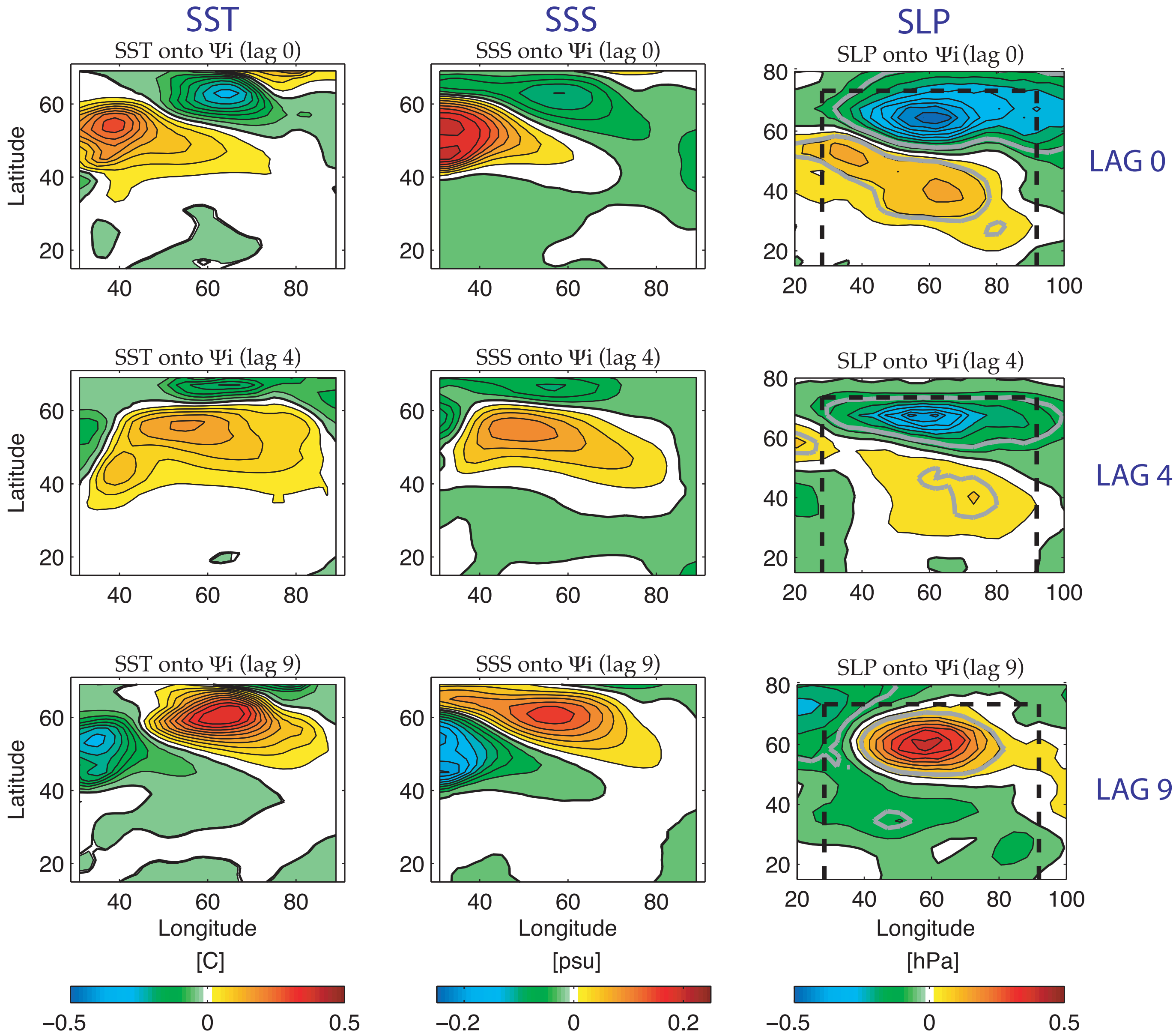


1. Time-mean MOC of 12 Sv with interdecadal anomalies of ∼20%
2. Significant peak at 20 yr period

EOFs suggest a propagating SST/SSS-Ψ oscillating mode (P$\sim$20yr)

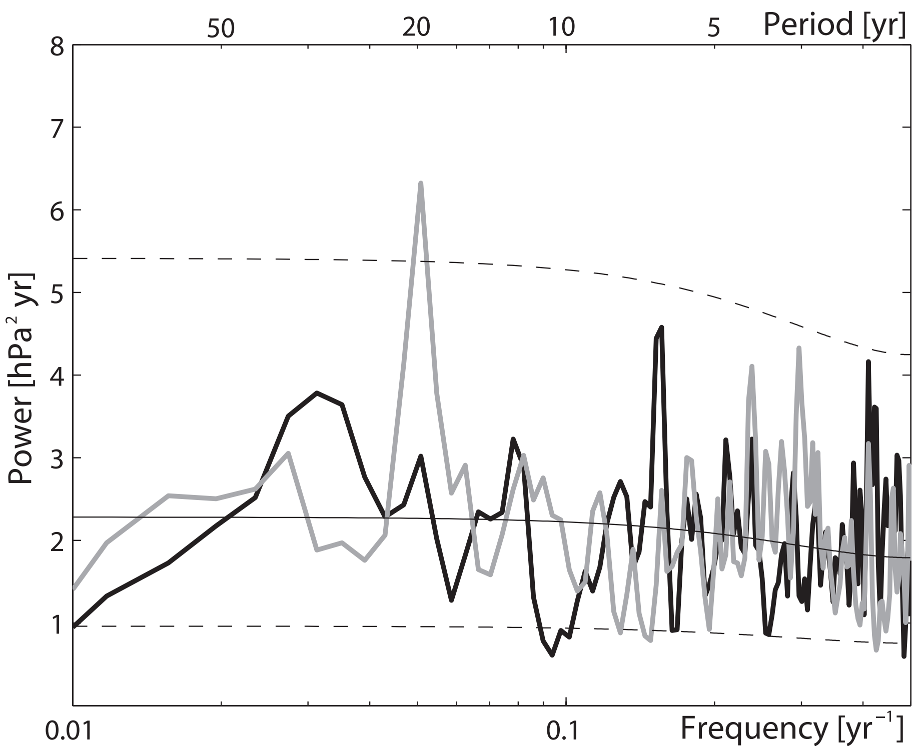


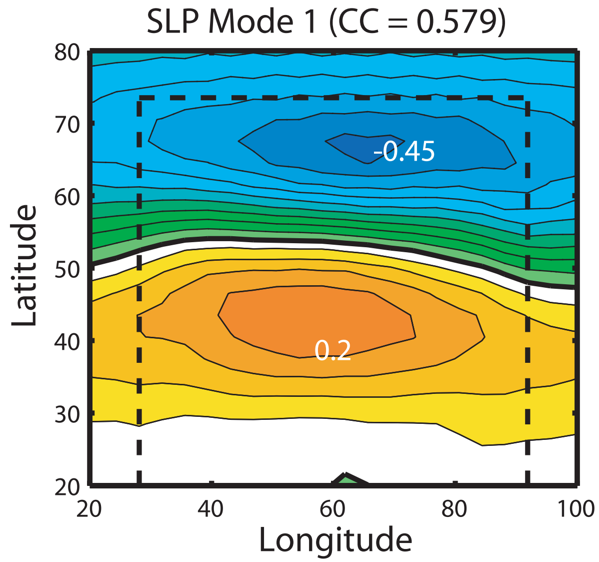
Regression of Ψ onto SST,SSS,SLP

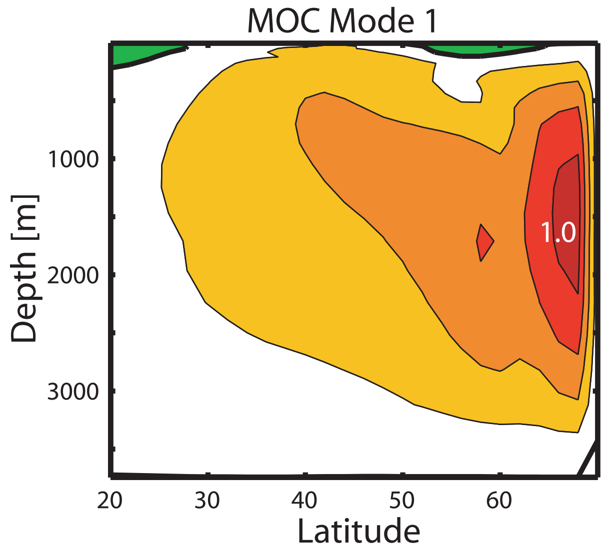


SLP and Ψ

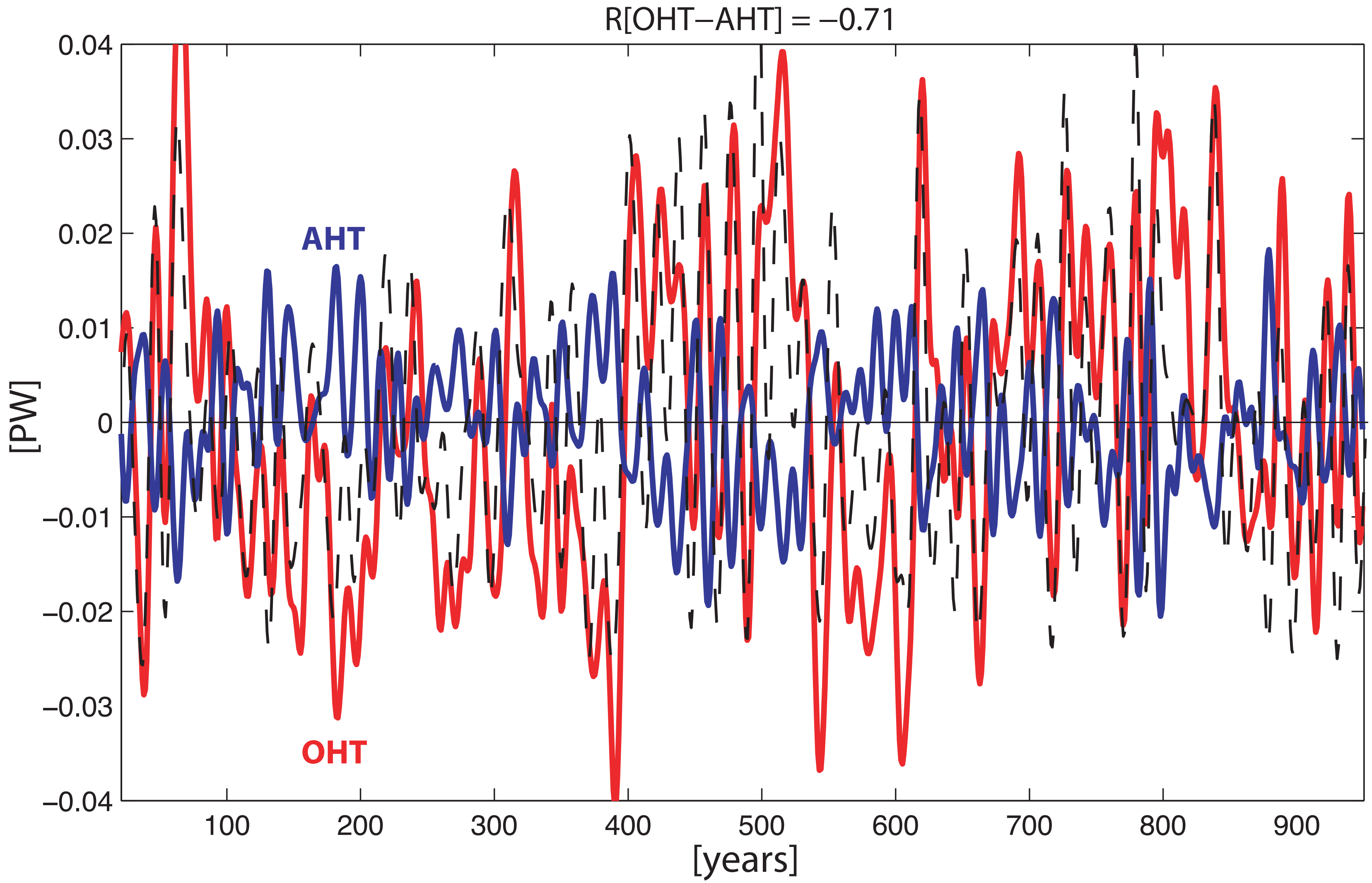
1. EOF2[SLP] (our NAO) has spectral peak at the period of the oceanic oscillation.
2. CCA reveals strong correlation between NAO state and Ψ oscillation at interdecadal periods.







Heat Transport Decadal Variability (I)

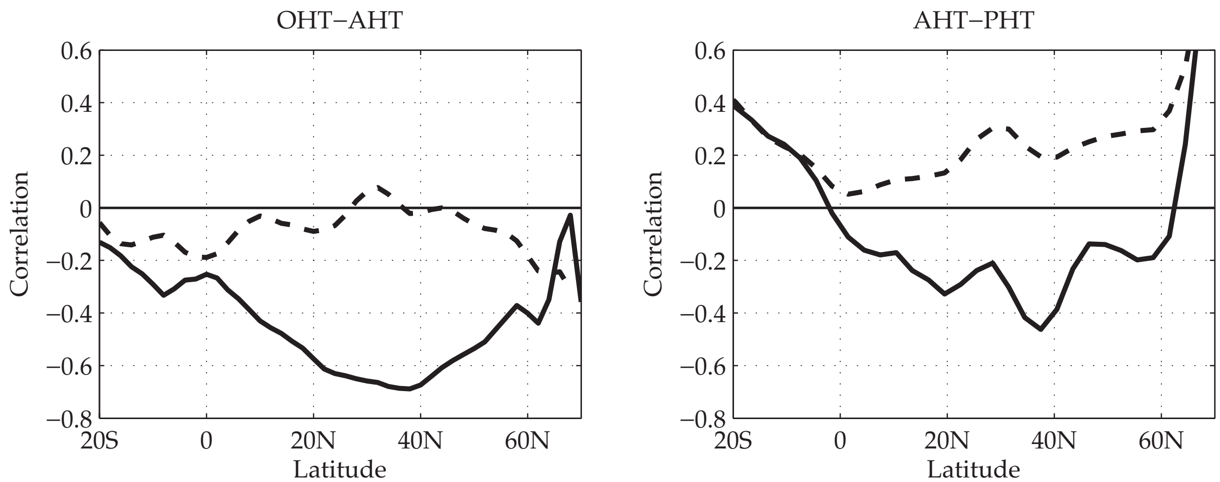


1. High level of compensation in Extratropics: OHTa = -AHTa
2. Ψ anomalies lead OHT anomalies

Heat Transport Decadal Variability (II)

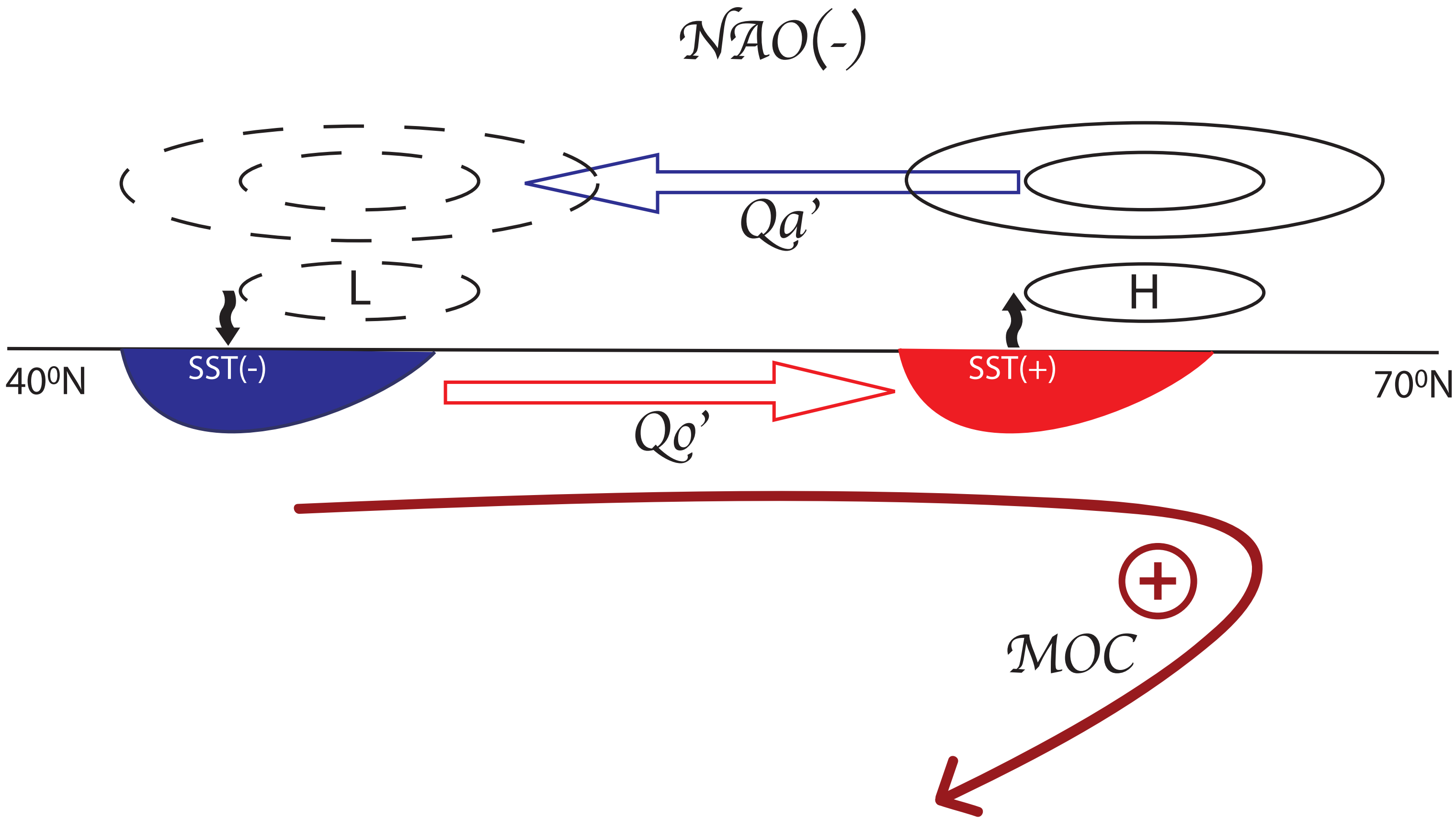
Bjerknes hypothesis:

If TOA energy flux and ocean heat storage ∼Constant
(decadal timescales & extratropics), then,
ΔAHT = -ΔOHT because:
+(Ψ/OHT)a yields to +SSTa → -baroclinicity and -AHTa.



1. High OHT-AHT anti-correlation (compensation); max at ϕ ∼40 where OHT peaks.
2. No compensation at annual periods and equatorial regions.
3. AHT seems to drive the system at annual time scales.

A Coupled Mechanism



⇒ The oceanic oscillation drives the atmosphere at the preferred period.

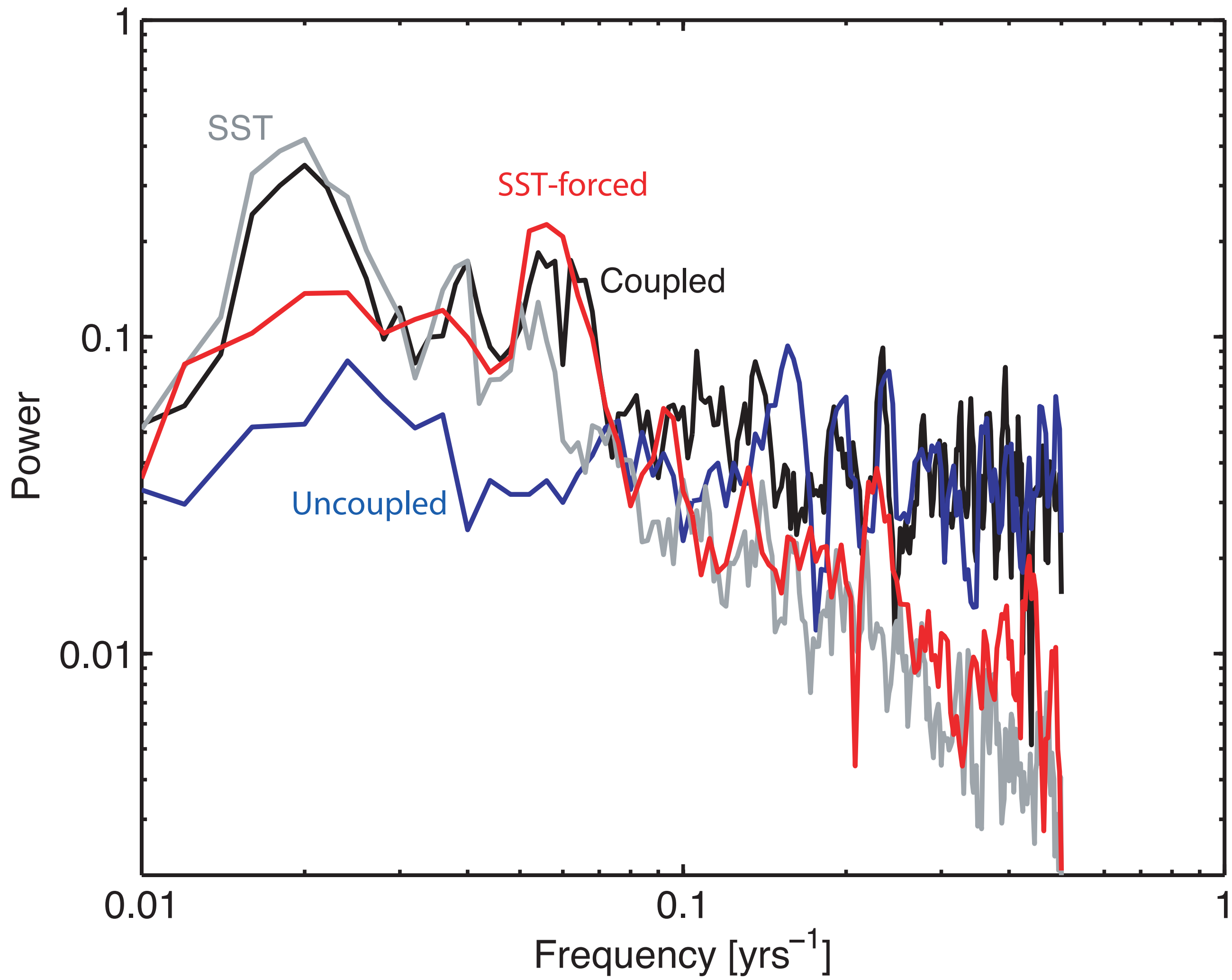
⇒ The atmosphere sustains the mode through *Reduced Thermal Damping* [Barsugli&Battisti, 1998] because of the good degree of thermal correlation at decadal time scales.

Uncoupled Experiments: Atmosphere-only & Ocean-only runs

Basic Questions:

1. Does the atmosphere really *feel* the SSTa?
2. Is the oscillation rooted in the ocean?
3. What is the role of the oceanic mean state?

Atmosphere-only (I)

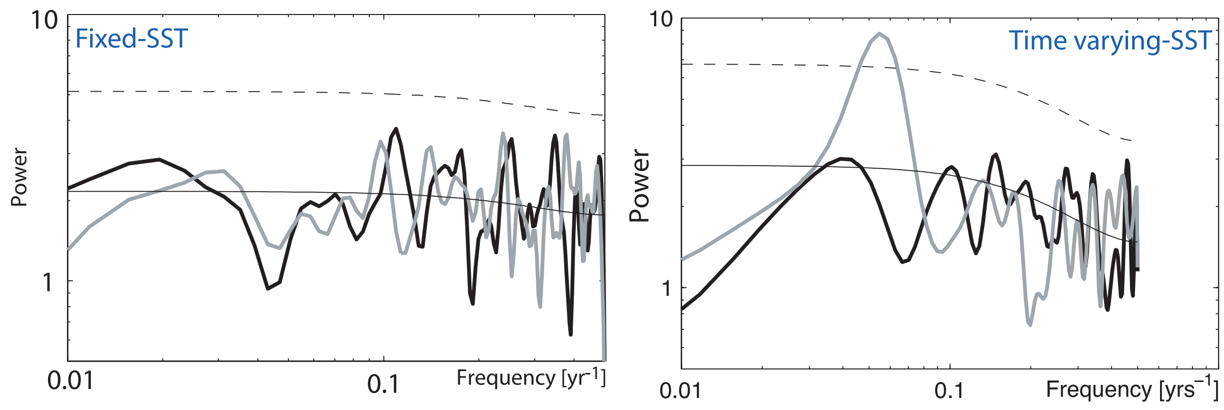


1. Ocean reddens the atmosphere at P>10 yr
2. but also LFV common peaks in ocean & atmosphere

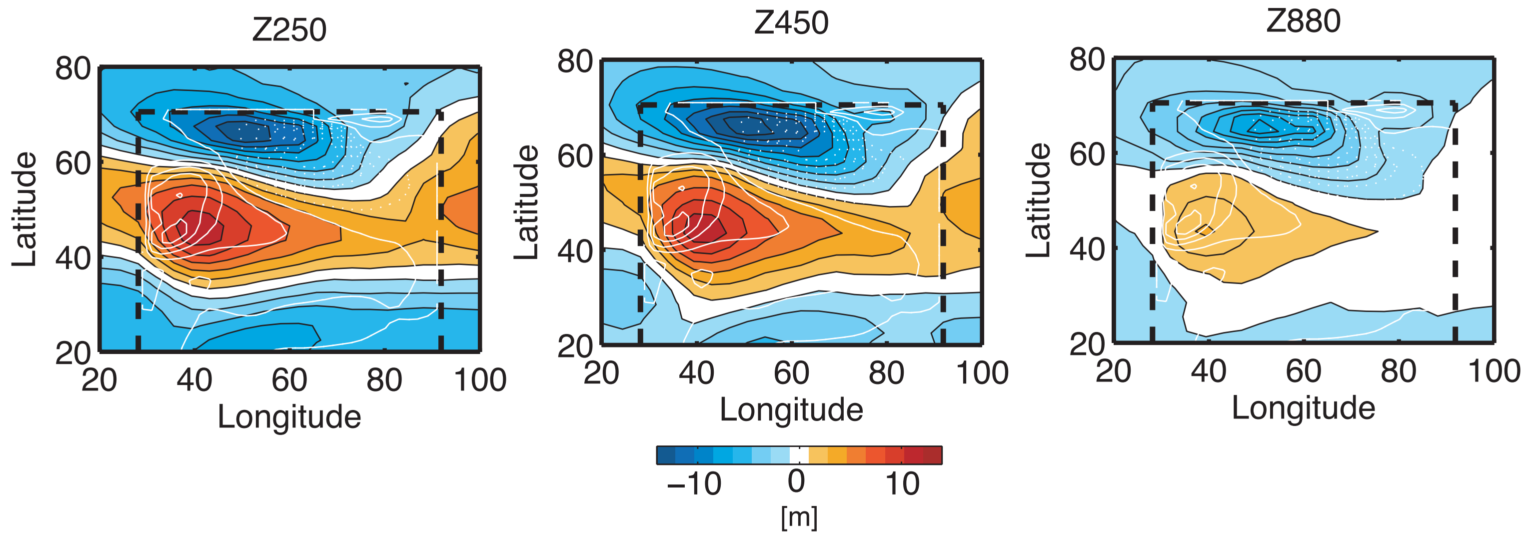
⇒ Coupling adds interdecadal variance to an intrinsic atmospheric mode

Atmosphere-only (II)

1. The atmosphere responds to the ocean on long timescales.



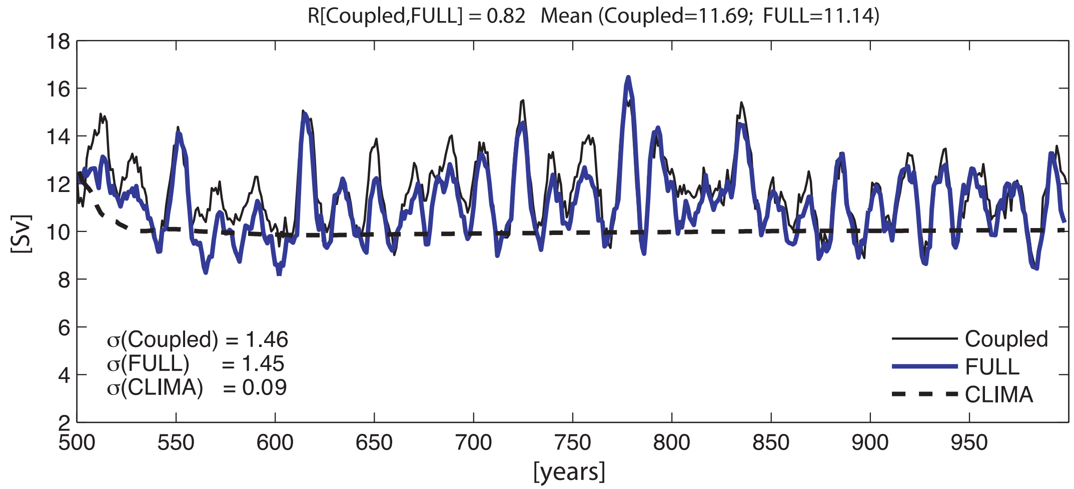
2. Atmospheric response is NAO-like, equivalent barotropic in structure.

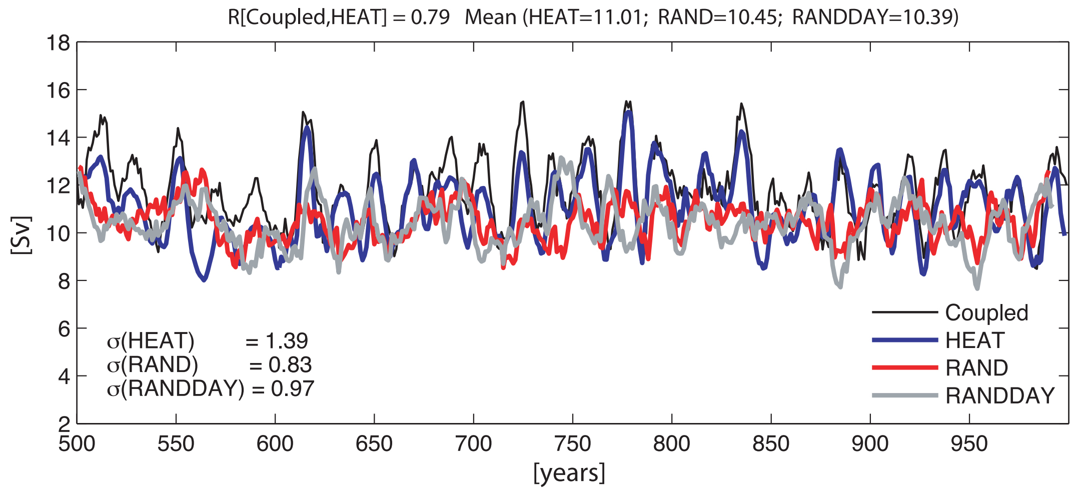


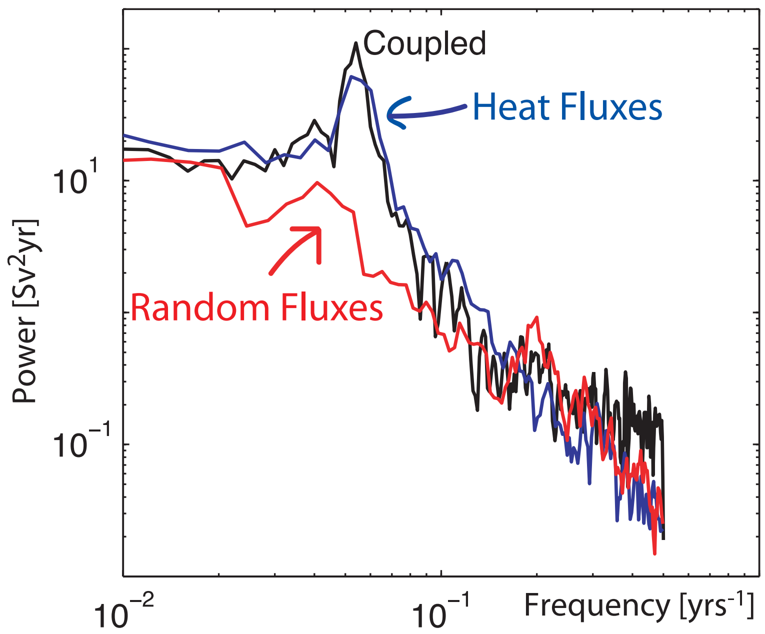
3. Recent CGCMs results support the idea of an atmospheric response to SSTa on interannual-interdecadal time scales [Bellucci et al., 2008; Msadek and Frankignoul, 2008]

Ocean-only (I): Control

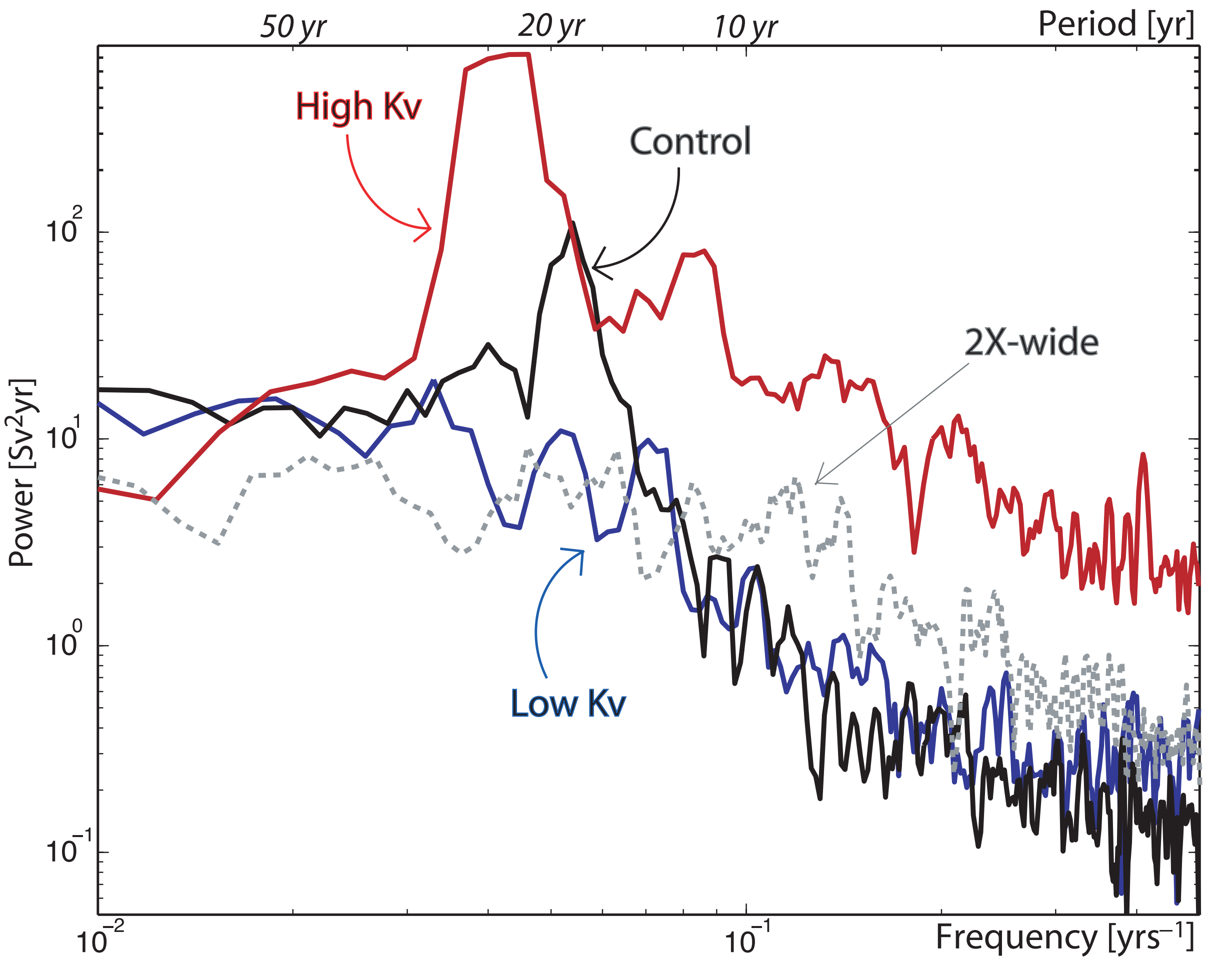
1. Oscillation is NOT self-sustained.
2. Heat Fluxes reproduce the oscillation (not surprising).
3. Stochastic forcing excites an interdecadal mode, but much weaker. ⇒ Coupling is fundamental





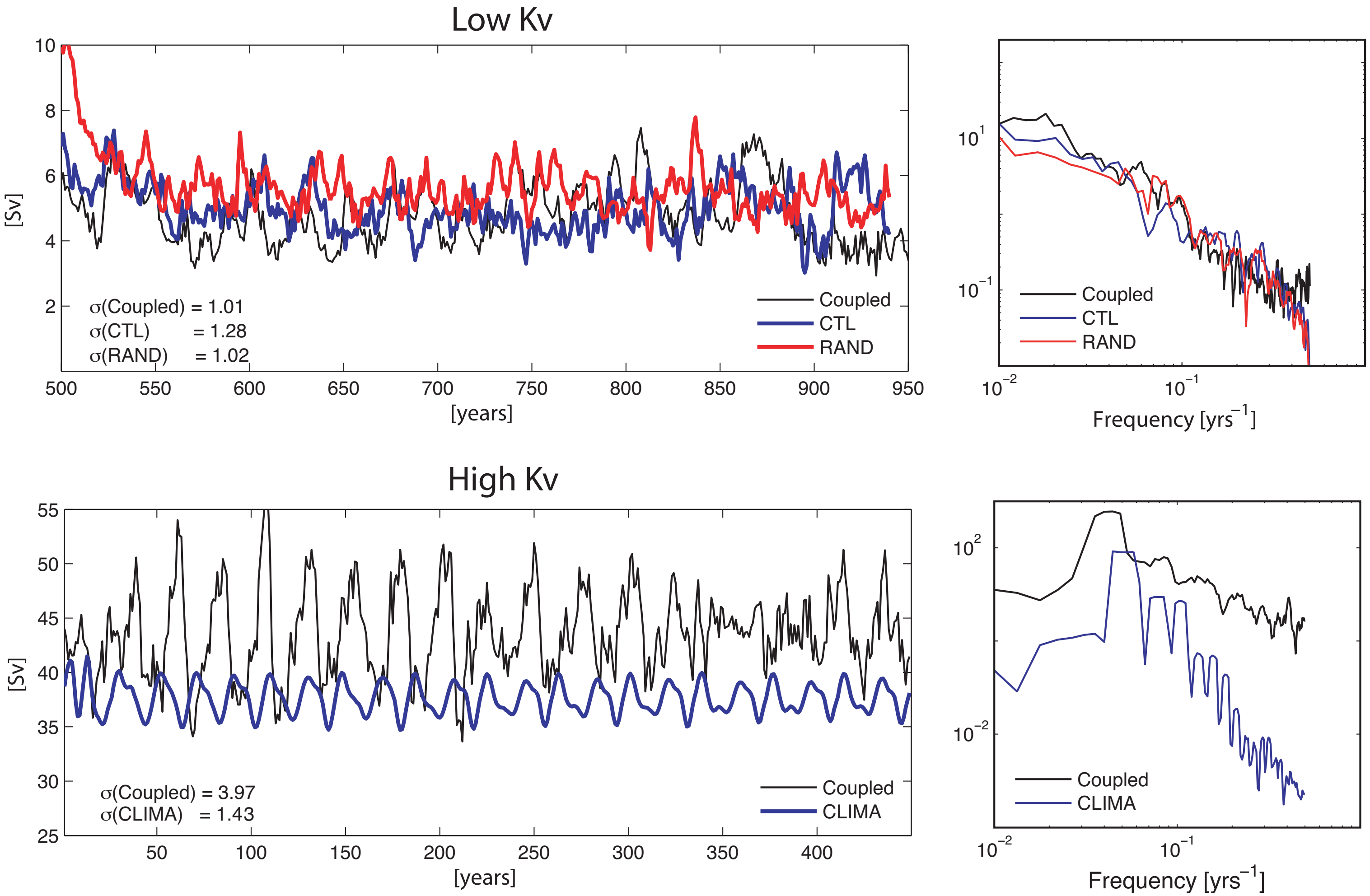


Dependency on the Oceanic Mean State



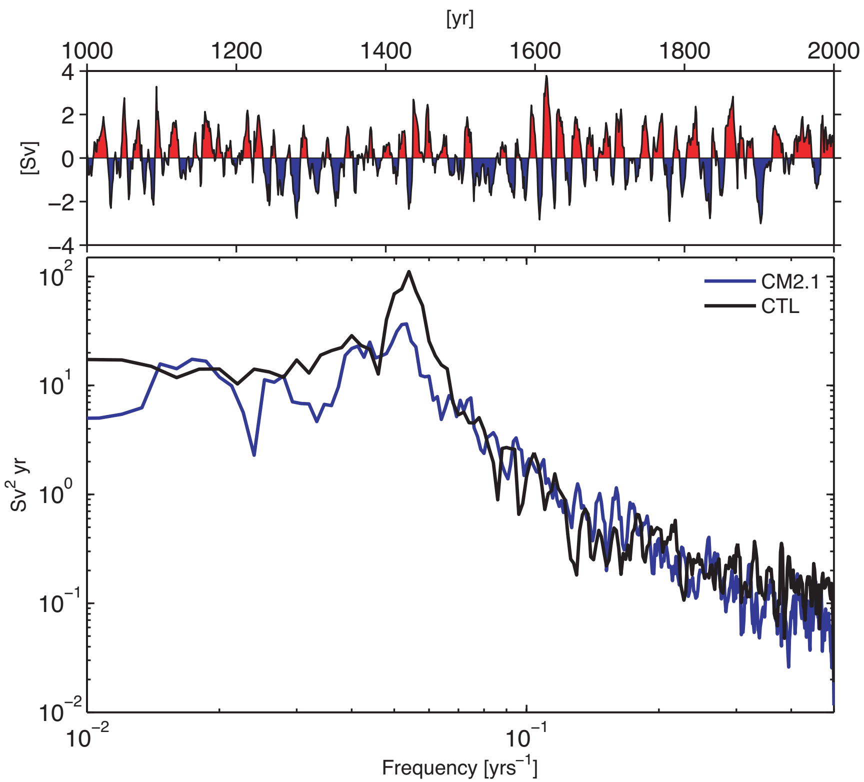
- Varying Kv or the geometry of the basin gives different oceanic variability.
- Hence, different atmospheric/coupled response = Self-sustained - Forced/Coupled - Red noise.

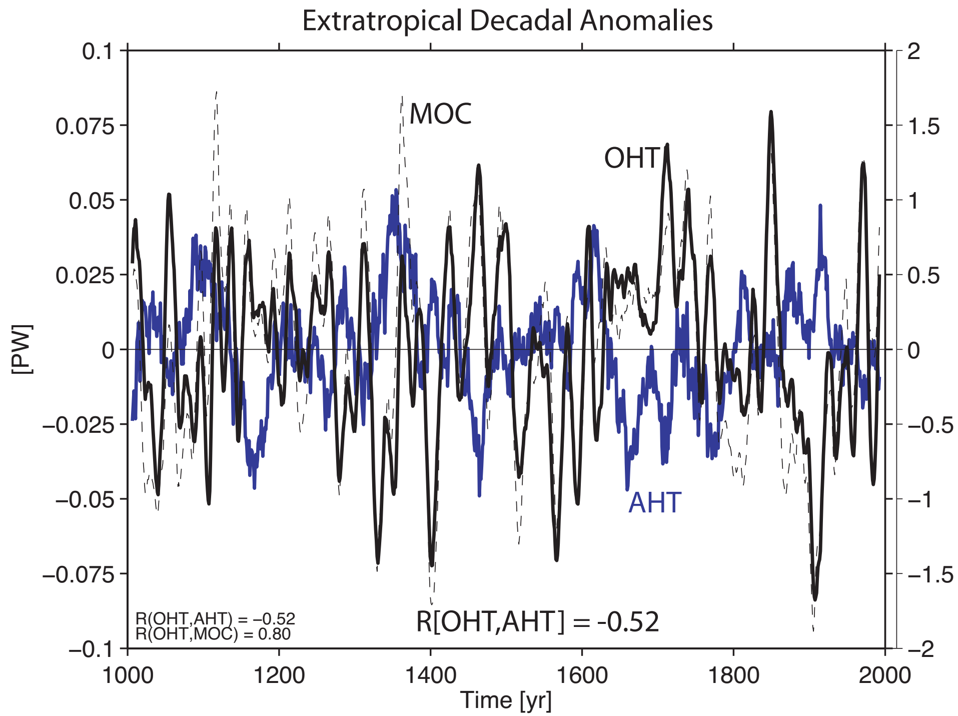
Dependency on the Oceanic Mean State



- Low-Kv: no preferred mode; no atmospheric response.
- High-Kv: no need for atmospheric coupling to sustain the oscillation; the atmosphere responds to the variability.

Relevance to an IPCC-class CGCM: GFDL-CM2.1





- CM2.1 has variability at similar periods.
- Good Energy compensation in Extratropics [20-70]N and for decadal anomalies (Bjerknes mechanism). Also found by Shaffrey&Sutton, 2006

Main Results

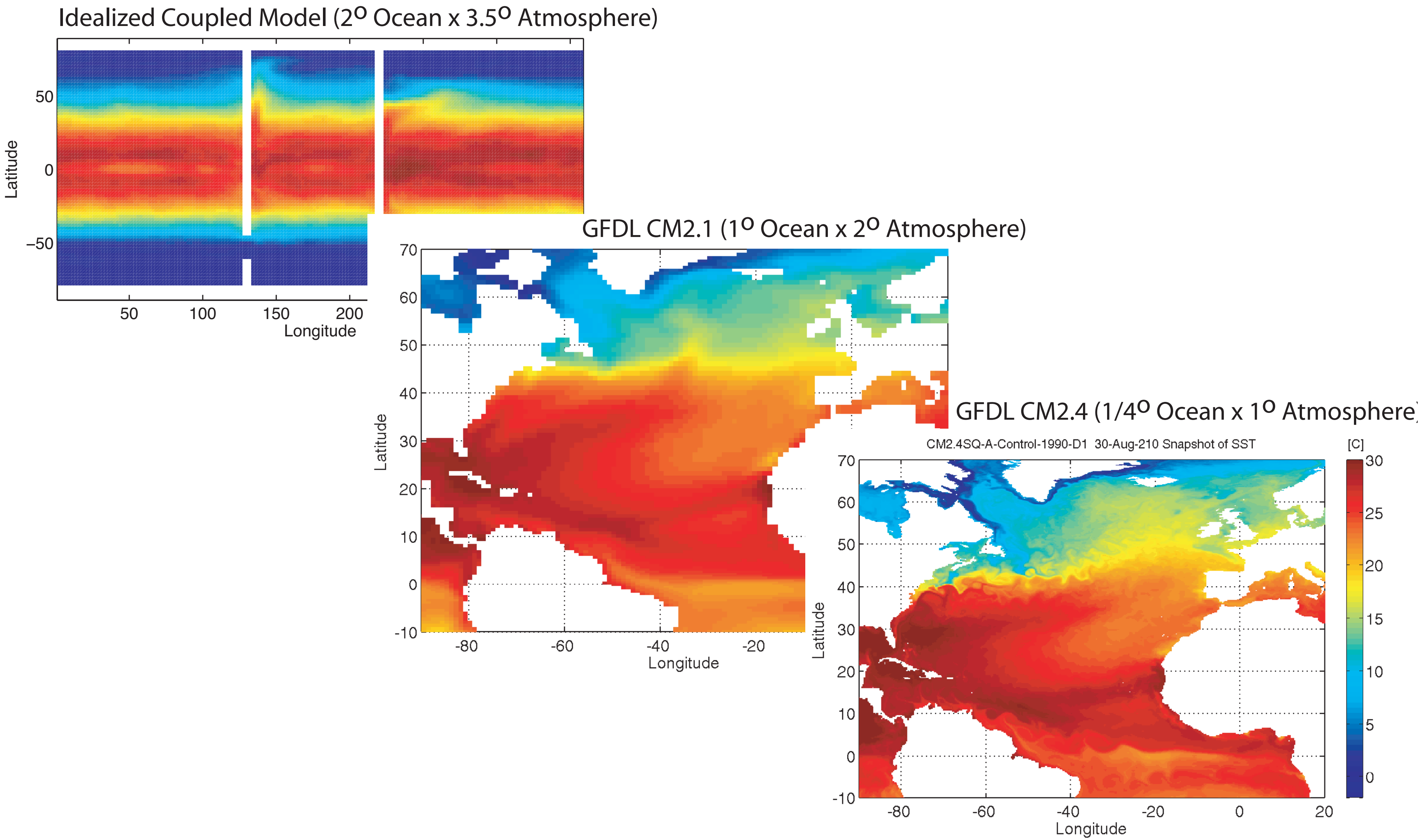
Conclusions

1. An oceanic interdecadal oscillatory mode of $\sim$20 yr was found to covary with the atmosphere. The damped oscillator drives the atmosphere at decadal periods. The atmospheric response helps sustaining the oscillation.
2. Bjerknes compensation is present in the model and is part of the coupled mechanism.
3. The mode projects onto an atmospheric mode (NAO) and this provides a positive feedback to the oscillation.
4. Coupling adds variance to the system and the atmospheric variability is modified at long timescales.
5. The nature of the oceanic mode and its ability to force the atmosphere depends dramatically on the ocean mean state.
6. The oscillation bears similarities to the one found in CGCMs and observations.

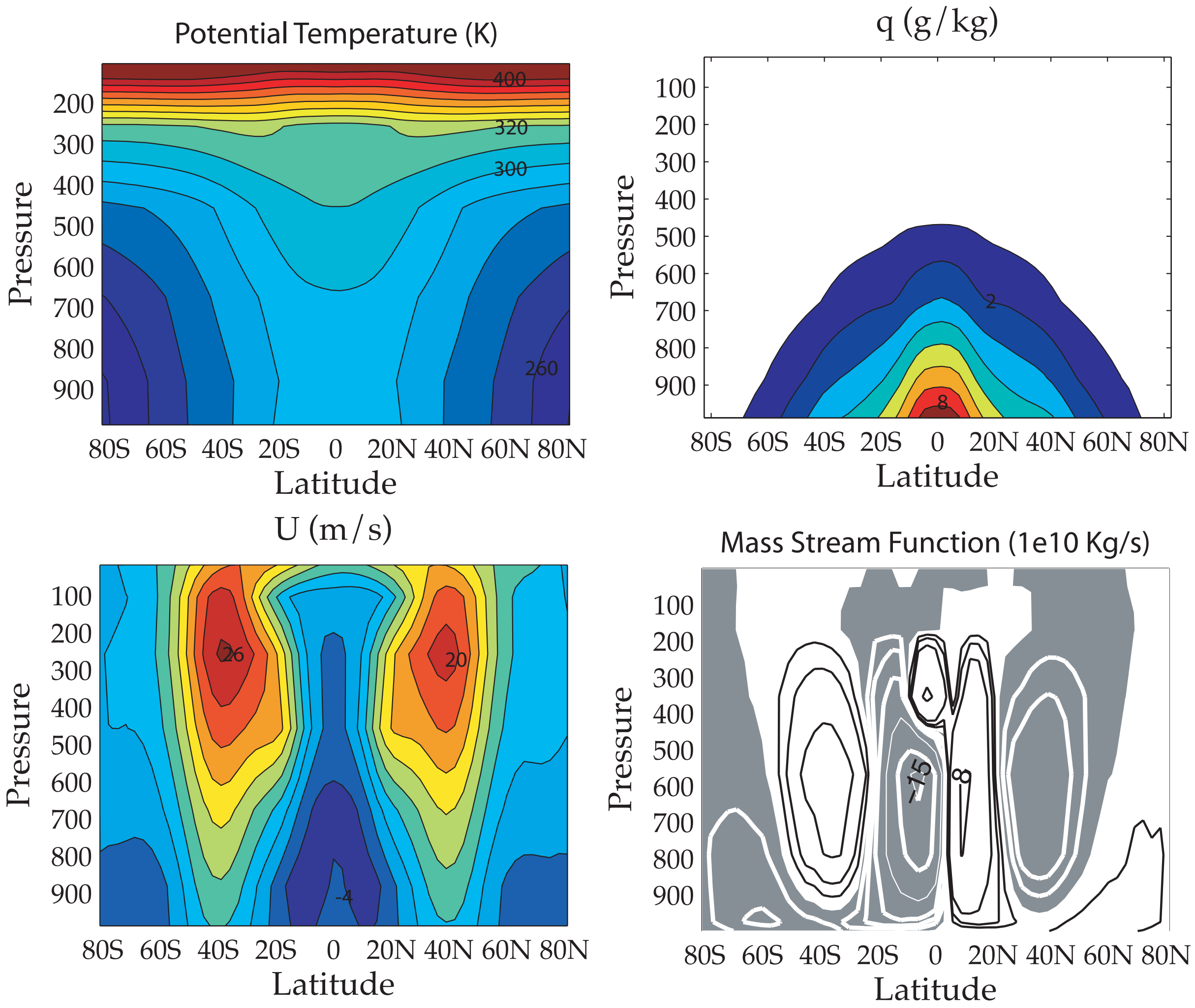
Future Studies

1. Inter-basins interactions.
2. Test with a hierarchy of Coupled models ...

Look at a Hierarchy of Coupled Models

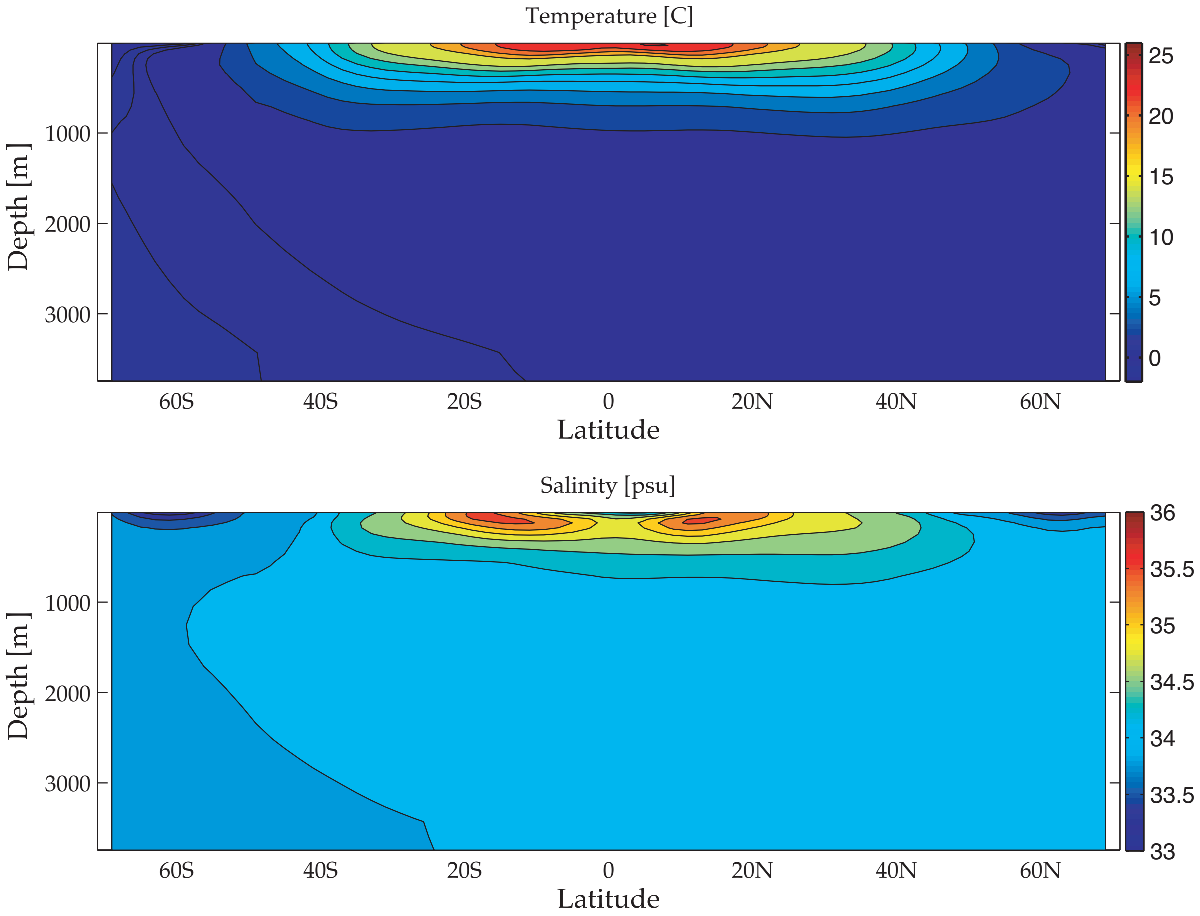


Climatology: the Atmosphere



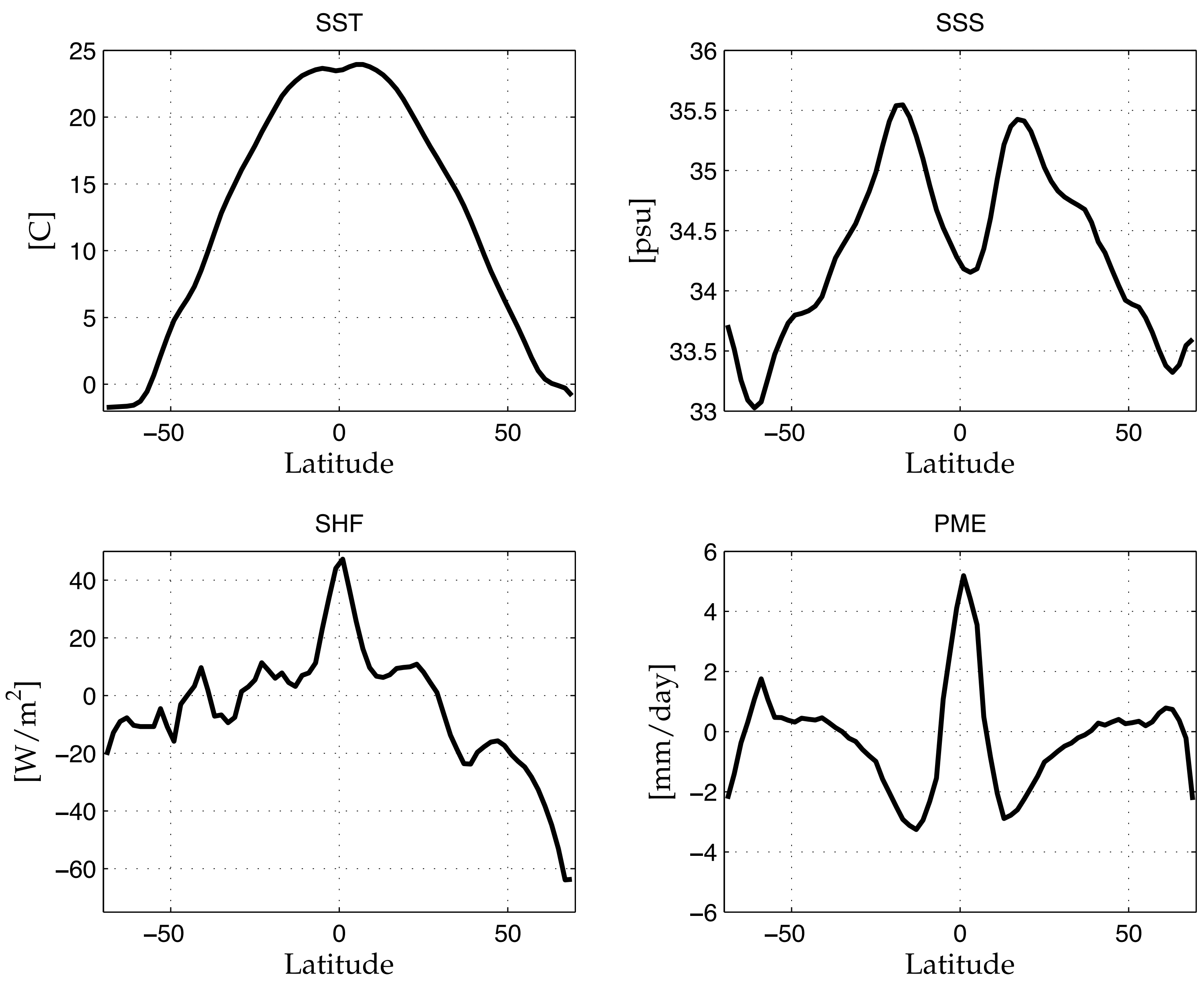
- Weak but present hemispheric asymmetry. No seasonal cycle.
- Realistic Hadley, Ferrel and poorly resolved Polar cells.

Climatology: the Ocean (I)

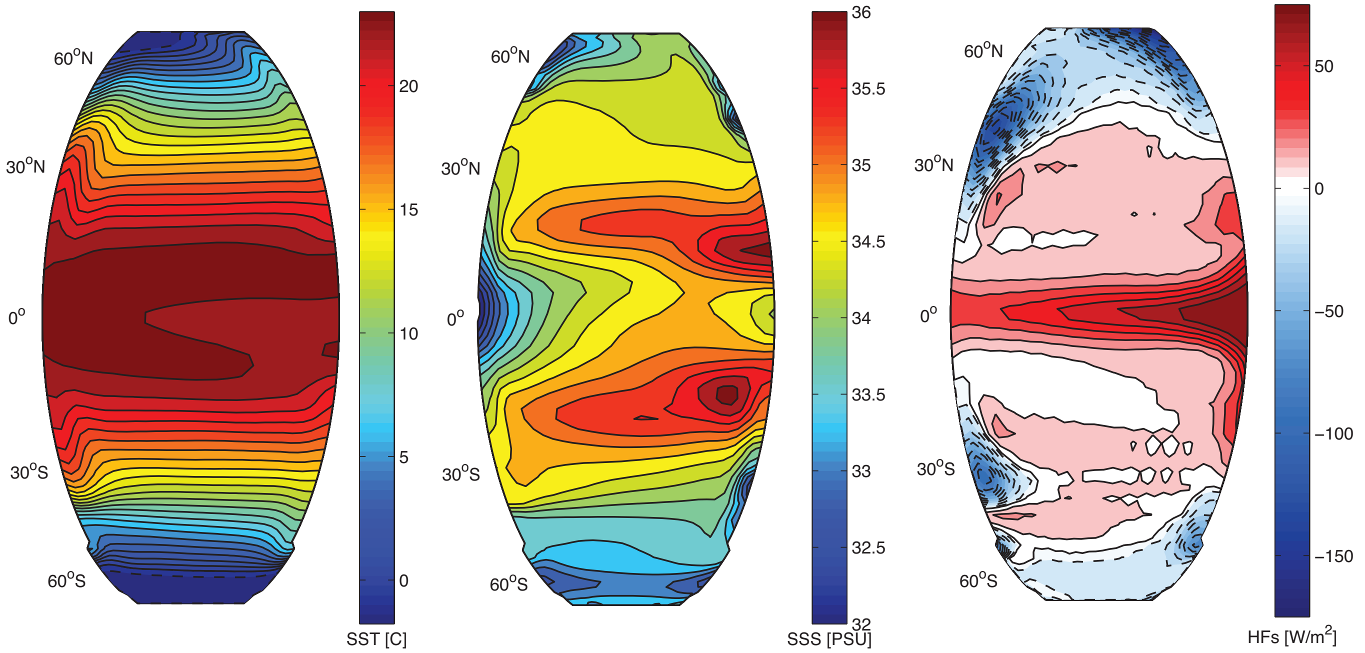


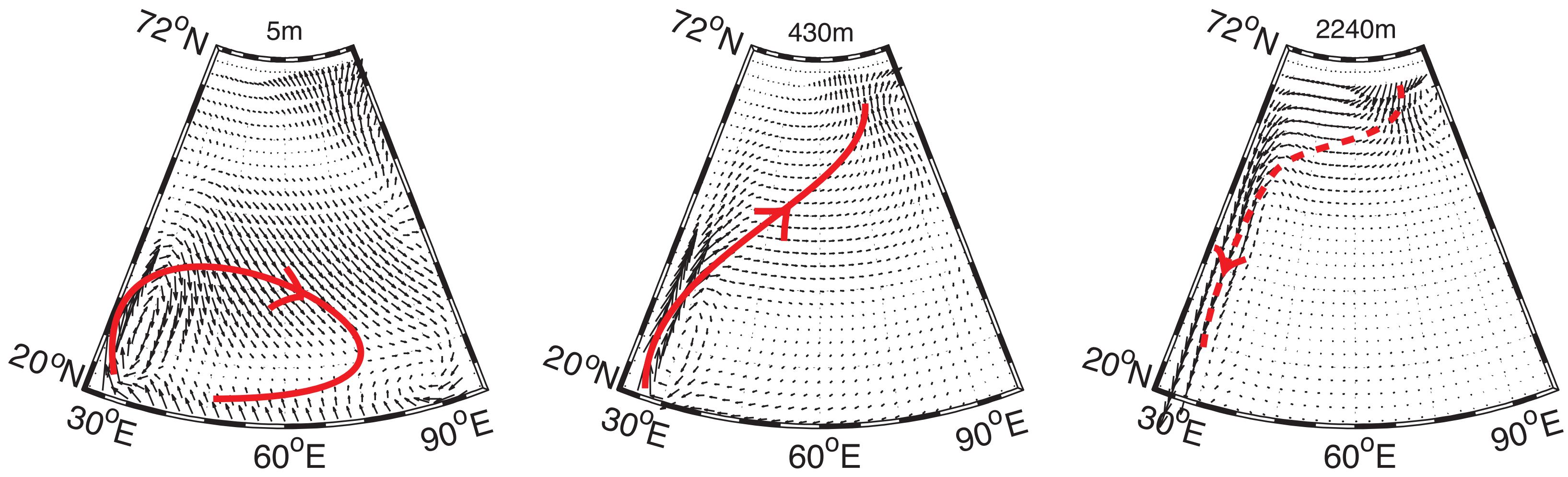
- A realistic, although overly diffusive, thermocline is maintained.
- Cold fresh waters are subducted in the southern hemipshere (our AABW). No AIW is formed.

Climatology: the Ocean (II)

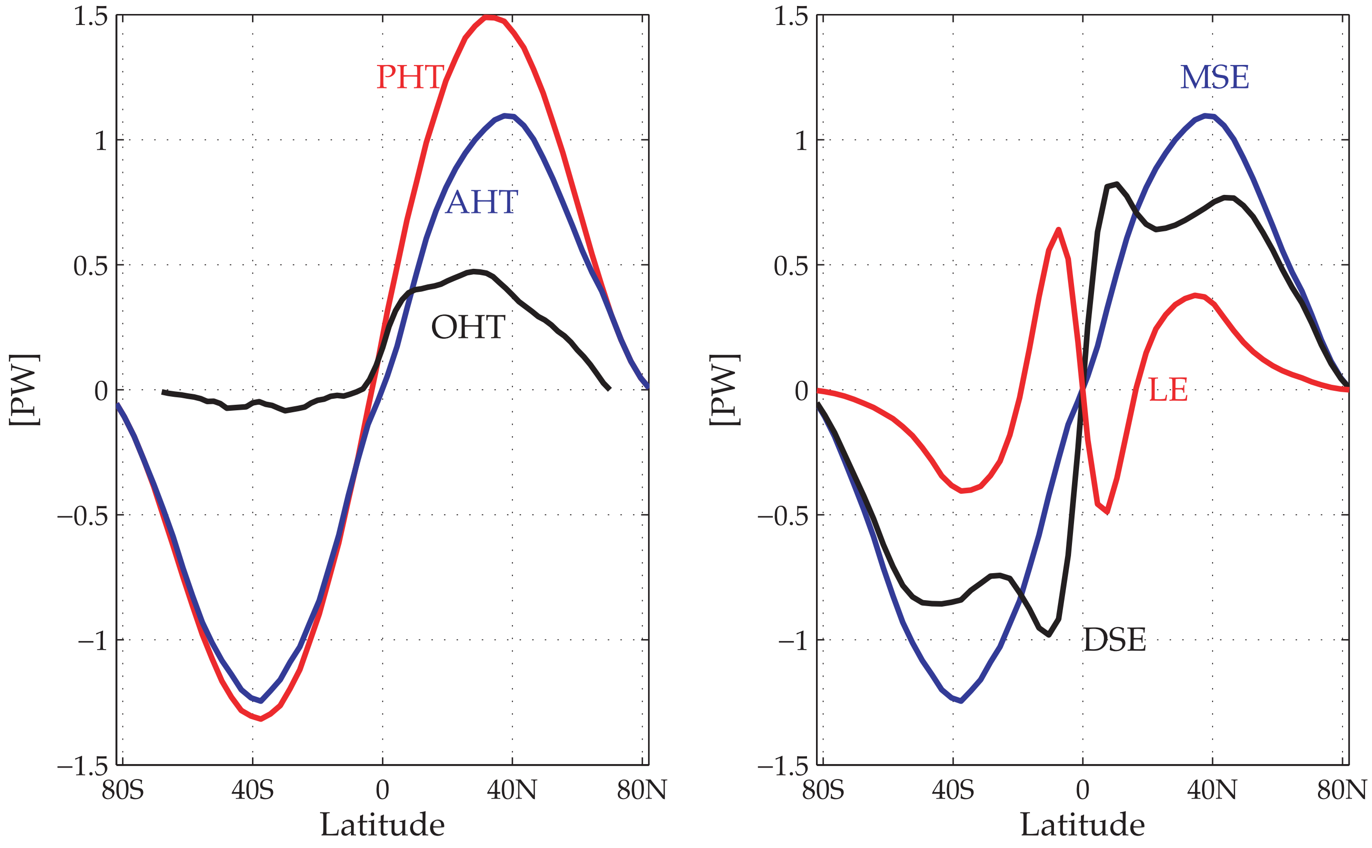


Climatology: the Ocean (III)



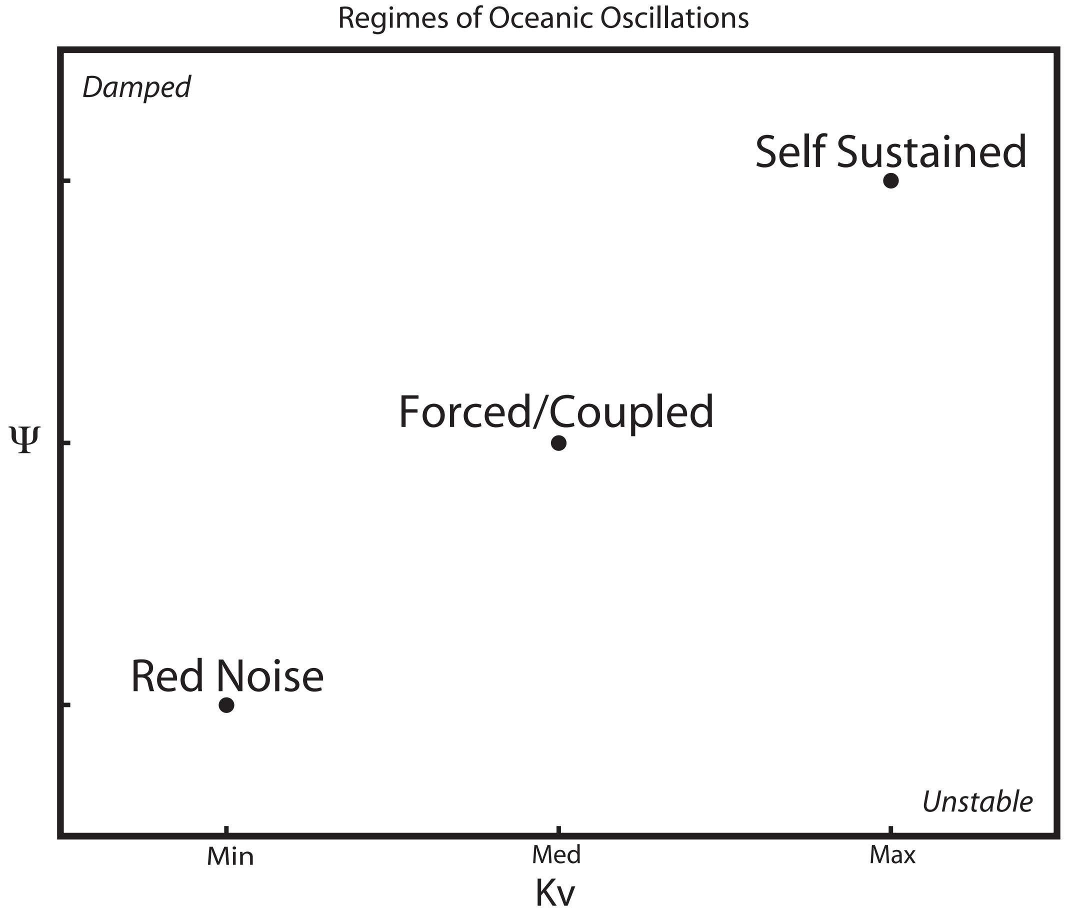


Meridional Heat Transport



- ✓ PHT∼1/3 of observations.
- ✓ OHT dominates in Equatorial regions. In middle latitudes AHT dominates.
- ✓ DSE compensates for LE in the Hadley cells.

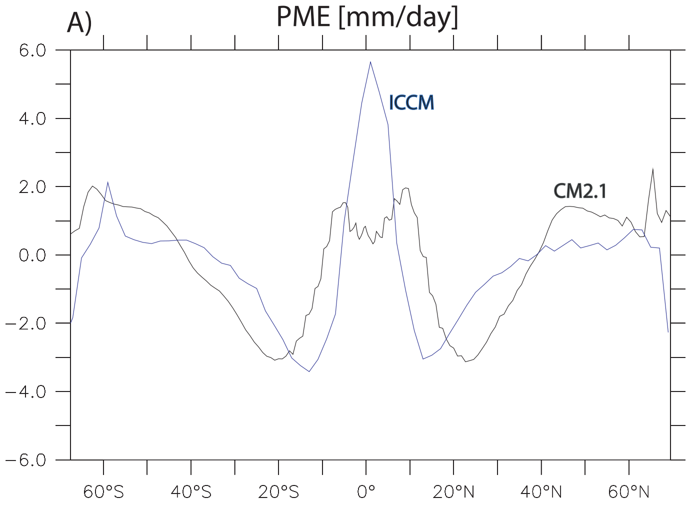
Regimes of Oscillations

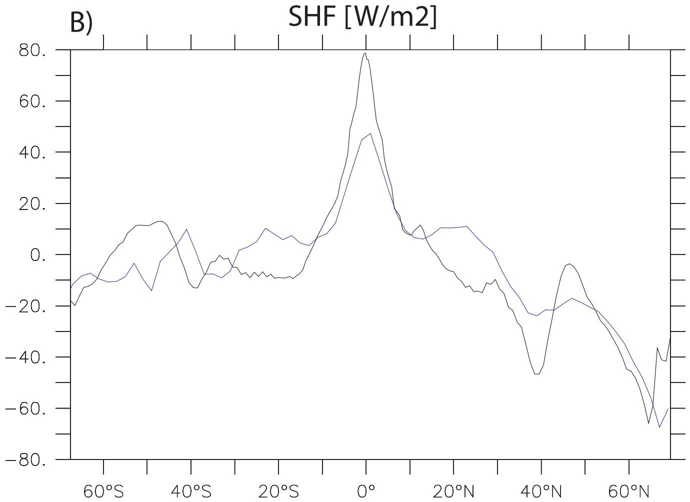


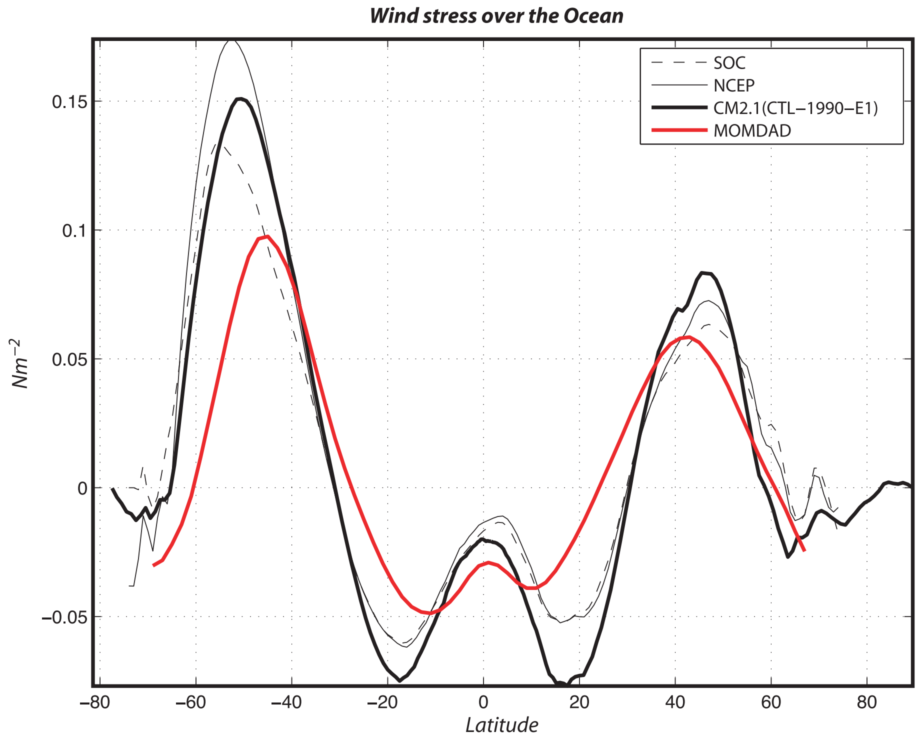
Depending on the oceanic mean state the response to coupling will be very different.

Ocean: Freshwater, Heat and Momentum fluxes

Comparison with CM2.1

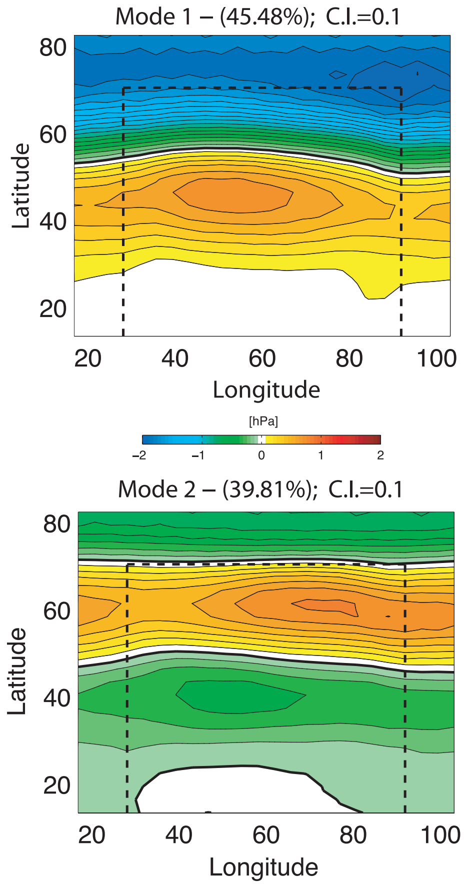


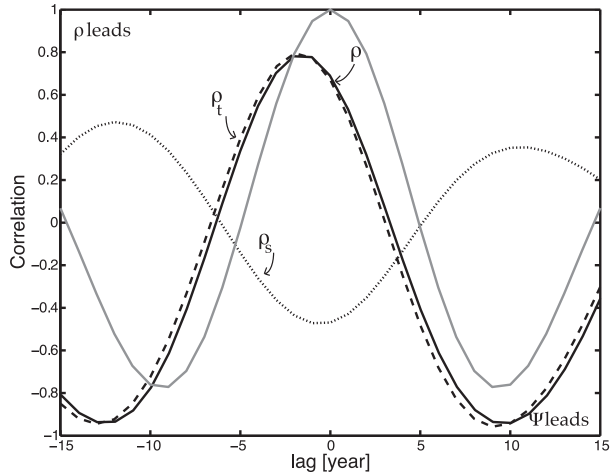


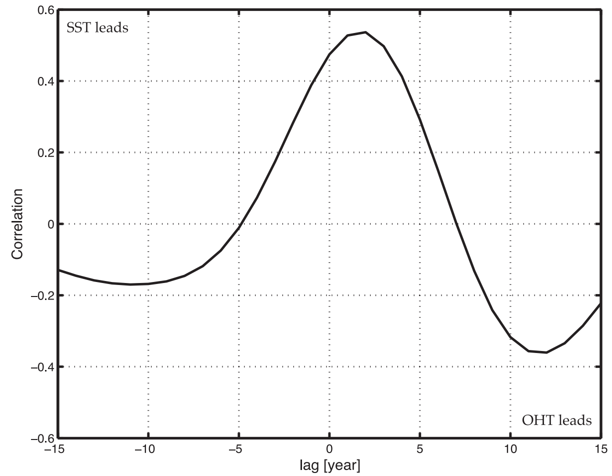


SST/SSS

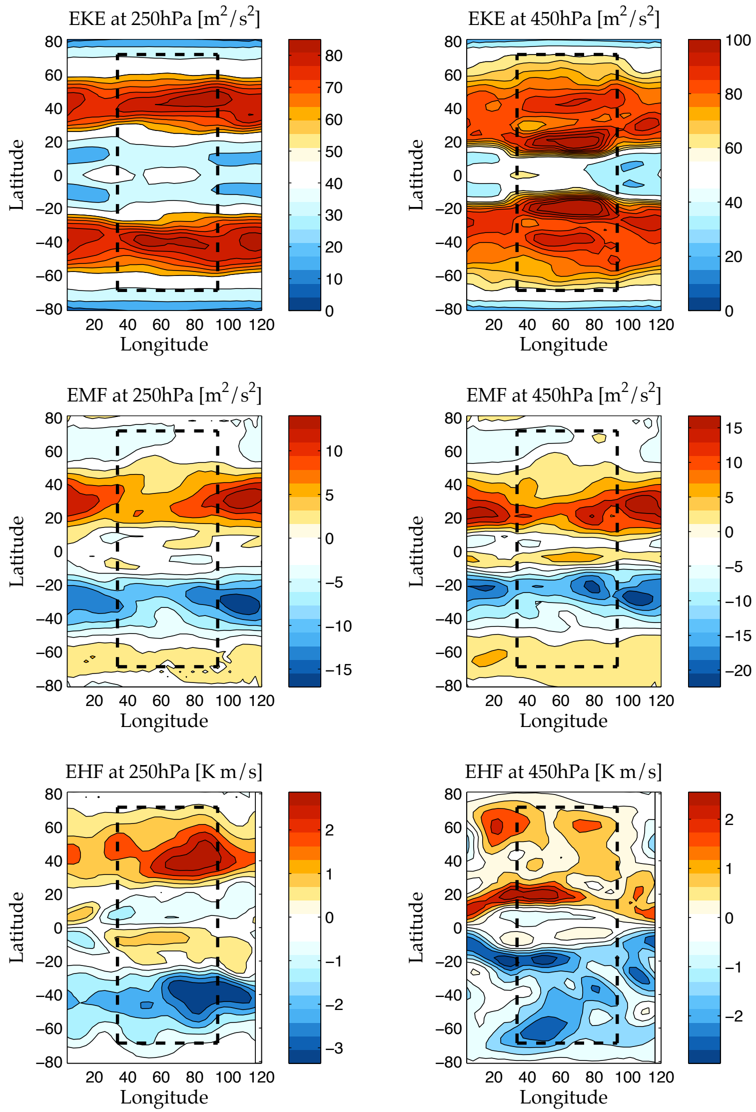
1. SST/SSS propagating pair in quadrature with P$\sim$20 yr
2. T contribution dominates ρ evolution
3. SST have oceanic origin (OHT leads by a few years)

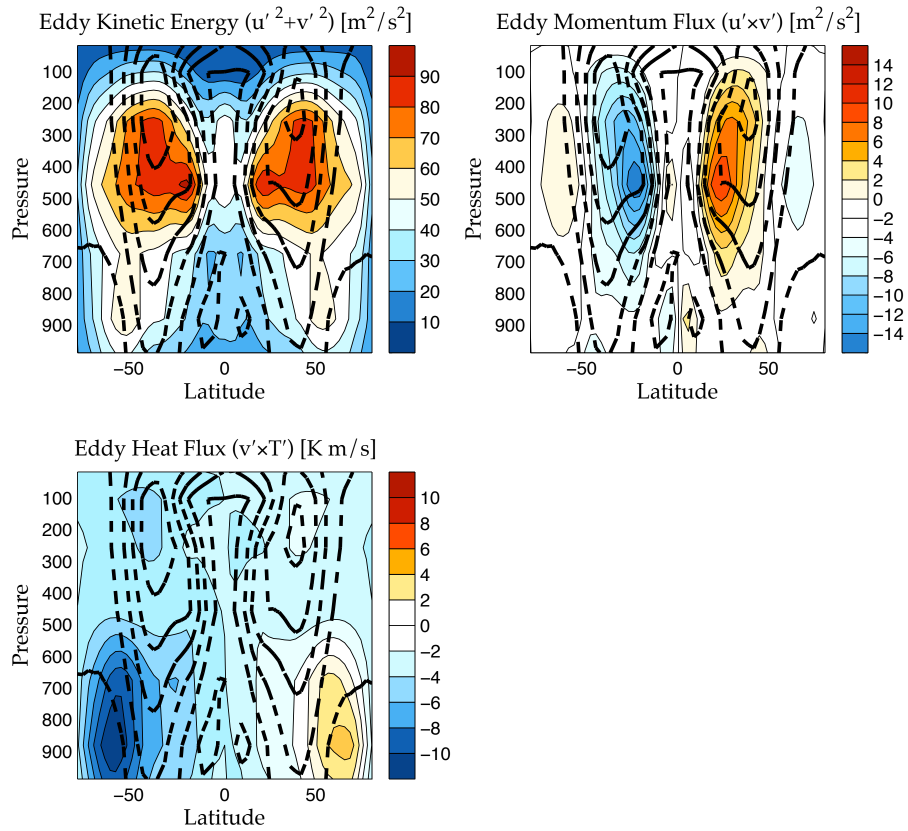




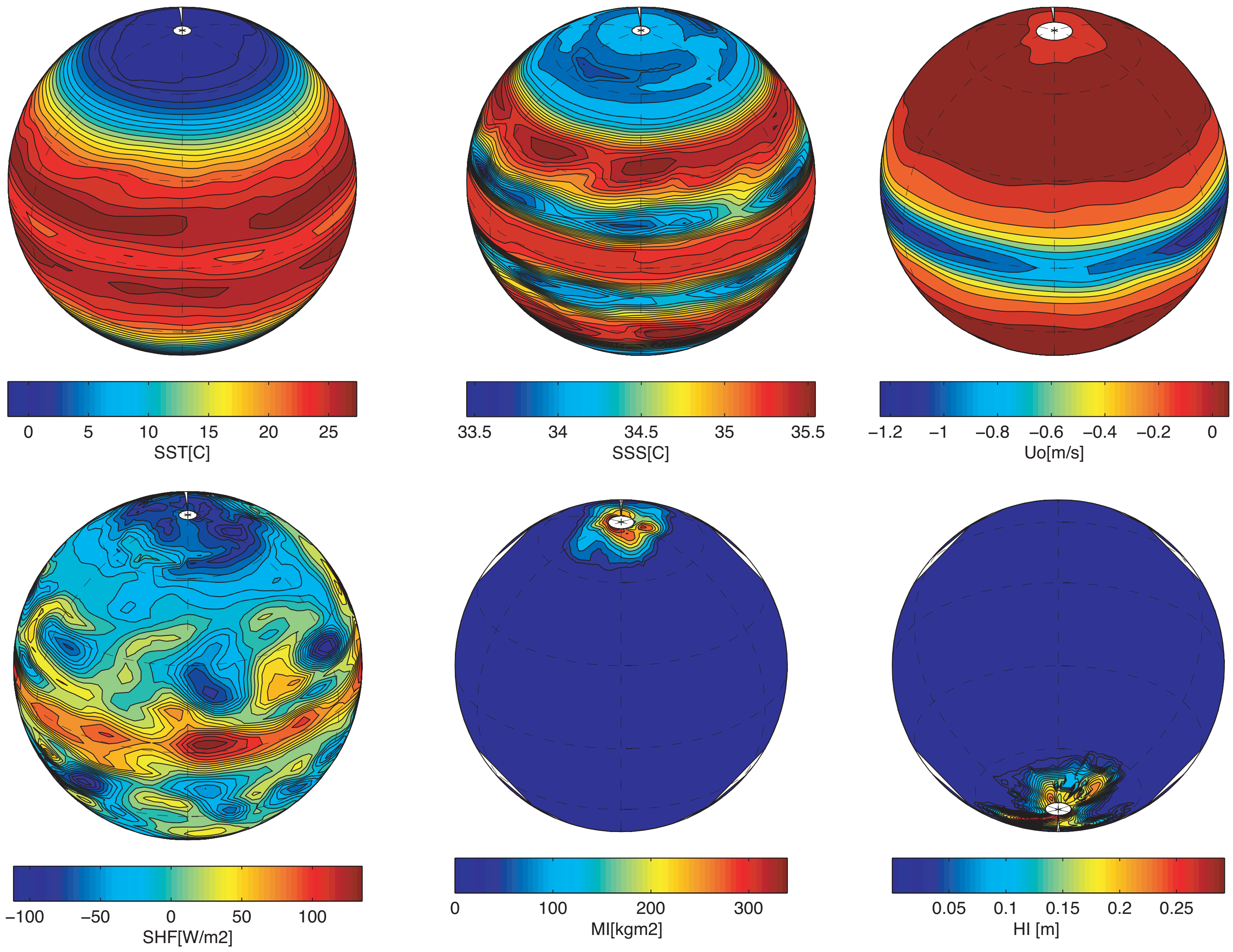


Atmosphere: Eddy Heat and Momentum Fluxes





Aquaplanet: some 20 yr of integration



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   Damped modes of the uncoupled ocean
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   The ocean is excited by the atmospheric variability
   Damped modes of the uncoupled ocean
3. Coupled modes of variability (Latif&Barnet, 1994):
   Non-trivial feedbacks between atmosphere and ocean (El Niño and in simple models).
   Unstable/weakly damped coupled modes
4. Intrinsic oceanic variability (Greatbatch&Zhang,1995):
   The ocean variability expresses itself spontaneously.
   Unstable modes of the uncoupled ocean