Examining the relationships between low-frequency SST and AMOC variability

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Thanks to the ECCO group, in particular Gael Forget and Patrick Heimbach

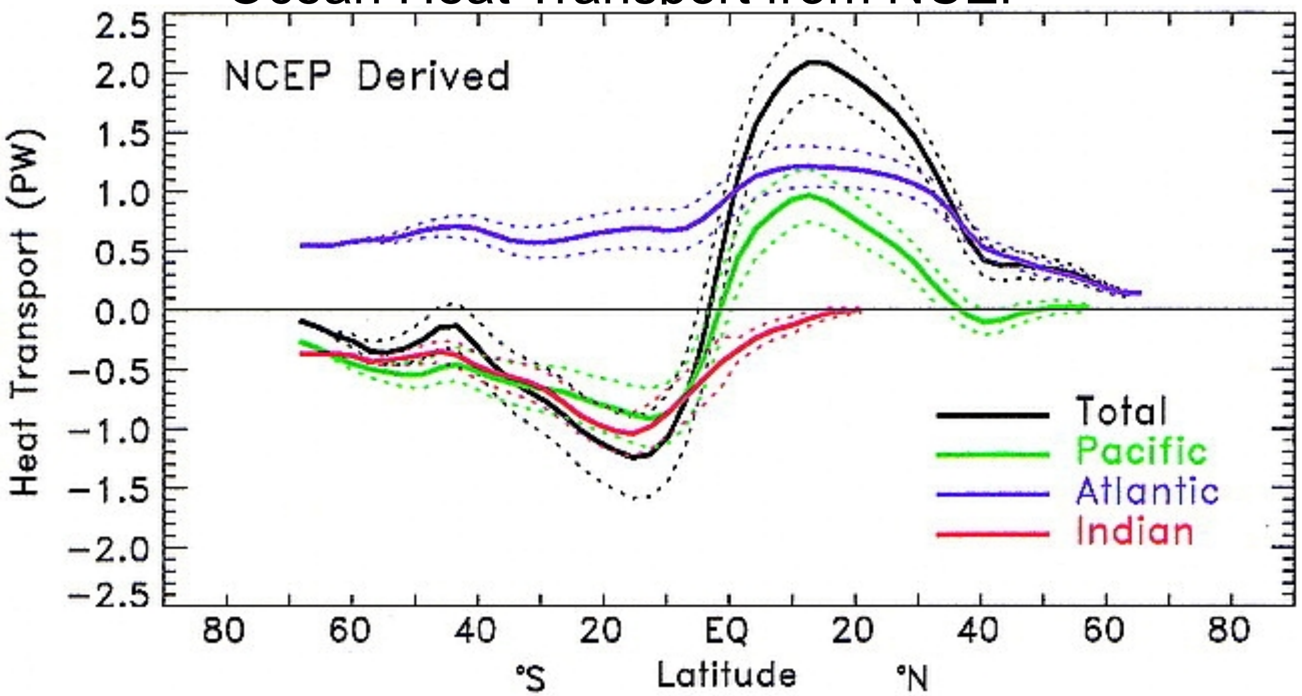
Low-frequency Atlantic SST variability

- Observations indicate Atlantic SSTs exhibit significant low-frequency variability.
- Impacts of Atlantic SST variability include:
  - Temperature, precipitation over adjacent landmasses (Zhang and Delworth, 2006, 2007; Pohlman et al, 2006)
  - Changes in frequency/intensity of hurricanes (Zhang and Delworth, 2006)
- However, the **origin** of SST anomalies is not understood.
  - Passive (local) response to atmospheric forcing.
  - Wind and/or buoyancy forced baroclinic Rossby waves (Sturges and Hong, 1995, 1998; Qiu 2002; Piecuch and Ponte, 2012).
  - Large scale changes in ocean heat transport due to changes in the AMOC and/or gyre circulations.
  - Lozier (2010): most significant question concerning the AMOC is role of AMOC in creating decadal SST anomalies.

Evidence for an active AMOC

- In the mean, the Atlantic Ocean transports 1.5 PW of heat northward.
- 60% of the peak ocean heat transport is associated with a circulation that reaches the cold waters of the abyss (Ferrari and Ferreira, 2012).

Ocean Heat Transport from NCEP



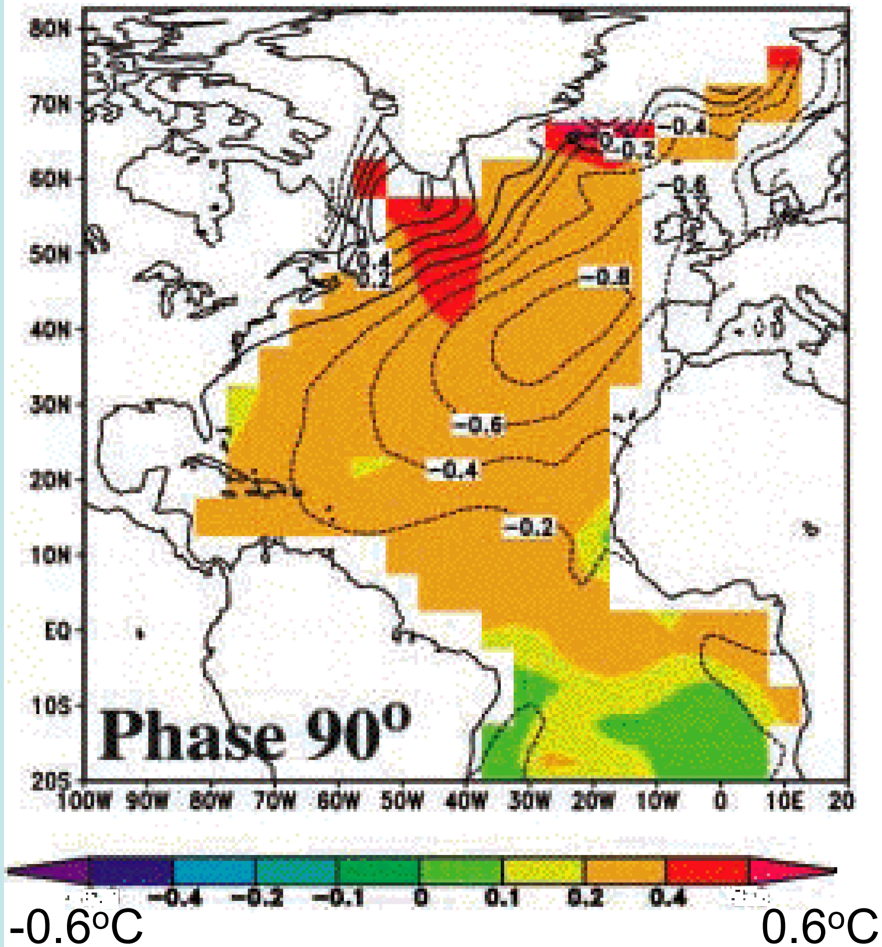
Trenberth and Caron, 2001

=> The deep MOC in the Atlantic plays a role in maintaining the current climate.

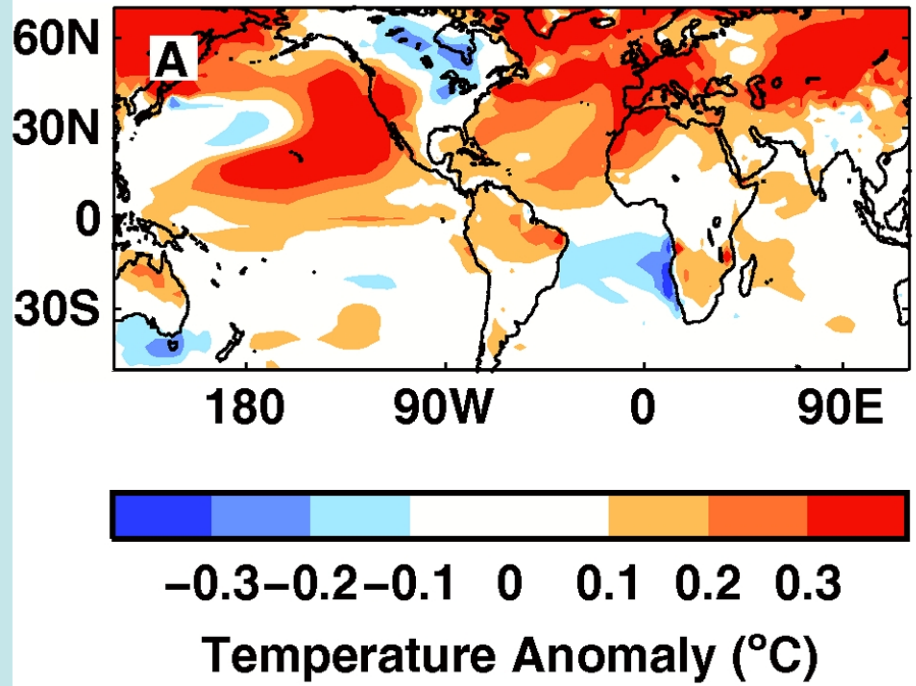
AMOC variability may play a role in climate variability.

Evidence for an active AMOC

Decadal AMOC variability => ocean heat transport => SST anomalies
(Bjerknes, 1964; Kushnir, 1994; Delworth, 1993; Delworth and Mann, 2000)



Decadal temperature anomalies in N. Atlantic from COADS obs. (Kushnir, 1997).



Surface temperature anomalies associated with a strong AMOC in 1400 year control run from HadCM3 (Knight et al, 2005)

Evidence for a passive AMOC

- **Correlation ≠ causation**: observed correlations between AMOC and SST in models may be simply due to the thermal wind relation.
- **Observations**: Wintertime SST variability over the last 4 decades can be explained as a local passive response to atmospheric forcing (Deser and Blackmond, 1993; Seager et al, 2000)
- **Idealized GCMs**:
  - Significant non-normal amplification of SST anomalies can occur without active participation of the AMOC (Zanna et al, 2011).
  - Buckley et al (2012): AMOC variability related to buoyancy anomalies on western boundary via the thermal wind relation.
    - Buoyancy anomalies originate in the subpolar gyre, and AMOC does not play a role in creating anomalies.
- **IPCC class GCMs**:
  - Buoyancy anomalies in NCAR CCSM3 due to fluctuations in subtropical/ subpolar gyre boundary--- linked to AMOC variability via thermal wind (Tulloch and Marshall, 2012) and convective variability (Danabasoglu 2008).
  - Lozier et al (2010): MITgcm initialized with observations from periods of buoyant/ dense N. Atlantic & concluded that AMOC changes not driving buoyancy changes.

Our Approach

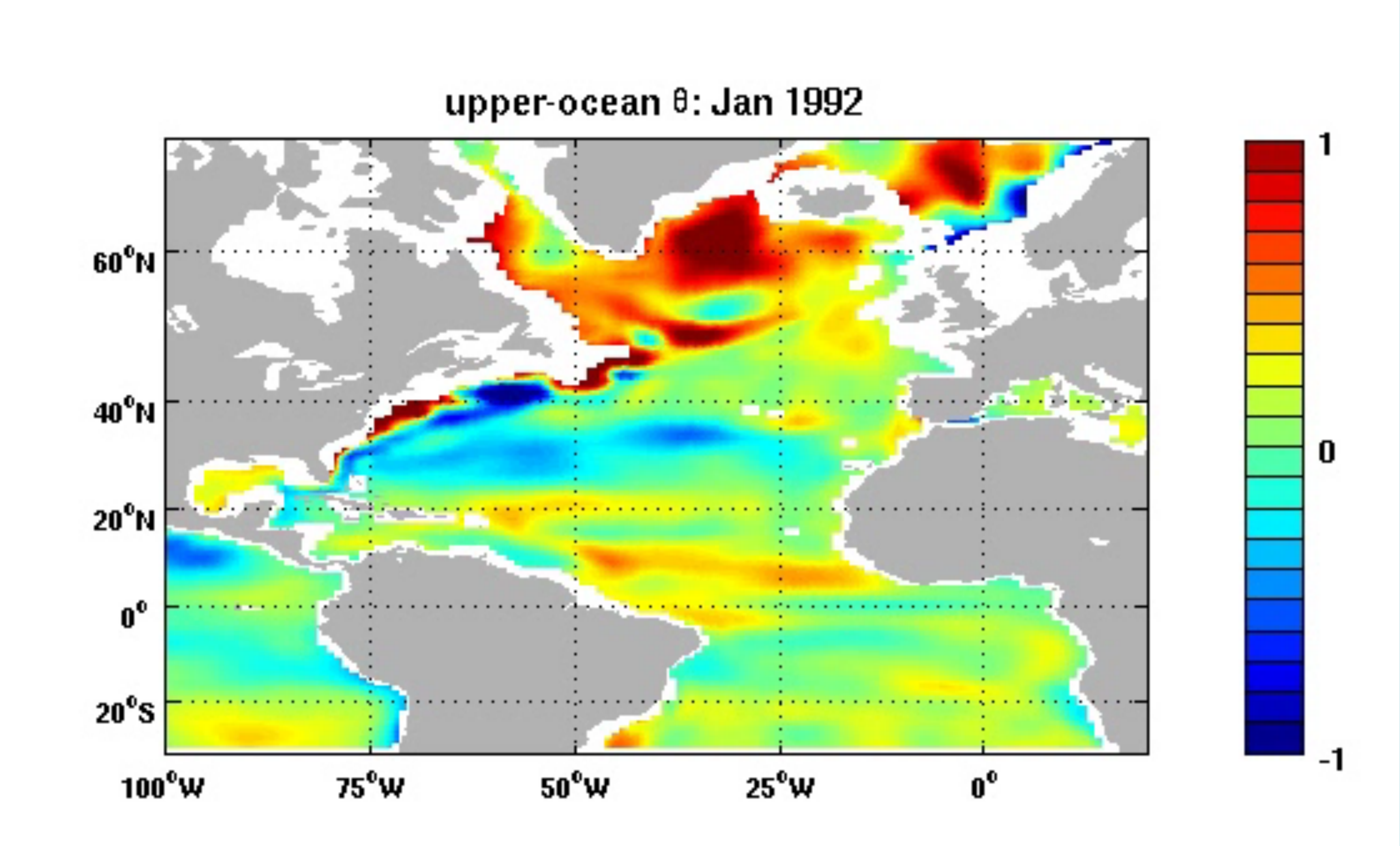
- Can low-frequency upper-ocean temperature variability in the Atlantic be explained by well understood processes?
  - Local atmospheric forcing (buoyancy and winds)
  - Rossby waves forced by wind/buoyancy forcing
- Answer will likely depend on timescale and region.
- If not, what other processes are important?
  - Changes in meridional ocean heat transport due to changes in the AMOC and/or gyre circulations?
  - Convection?
  - Non-linearity?
- Simple, null hypothesis for evaluating the role of the AMOC in low-frequency upper-ocean temperature variability.

Model: ECCO version 4 state estimate

- Estimating the Circulation and Climate of the Ocean (ECCO) state estimate
- MITgcm least squares fit to observations, 1992-2006
- For details, see P. Heimbach's talk or Forget et al, in prep.
- new global grid LLC_90
  - includes the Arctic
  - telescopic resolution to 1/3° near the Equator
  - meridionally isotropic in mid-latitudes
- shift from 23 to 50 vertical levels with partial cells
- forcing using ERA-Interim
- state-of-the-art dynamic/thermodynamic sea ice model
- nonlinear free surface + real freshwater flux B.C.s
- third-order advection scheme
- removal of C-D scheme for Coriolis terms
- use of diffusion operator (Weaver & Courtier, 2001) for in-situ obs.
- all satellite data are daily along-track
- internal model parameters are part of the control space

Upper-ocean temperature variability

Potential temperature anomalies averaged over top 500 m



Can we understand these upper-ocean temperature anomalies?

- **Baroclinic Rossby wave model**
- **Rossby wave model phrased in terms of baroclinic pressure anomalies (related to ρ by hydrostatic relation)**

Baroclinic pressure: modal decompostion

What portion of the variability is captured by 1st baroclinic mode?

- Equations of motion linearized about a resting mean state, flat bottom
- Separation of variables ➔ eigenvalue problem for vertical structure (Gill, 1982).
- Vertical structure for pressure:

$$\frac{d}{dz}\left(\frac{f_o^2}{N^2}\frac{dF_n}{dz}\right) + K_n^2 F_n(z) = 0$$

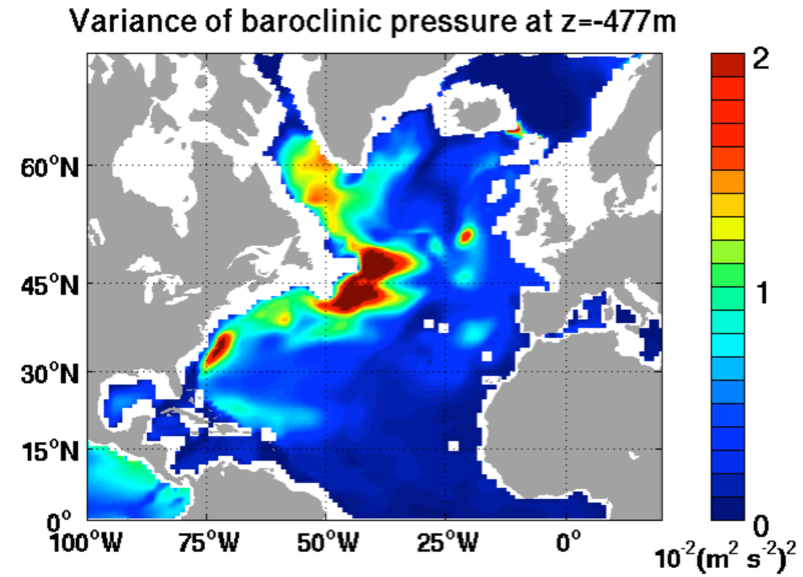
- Solve for F(z) at each horizontal location using observed N(z).
- Modes = complete, orthonormal basis

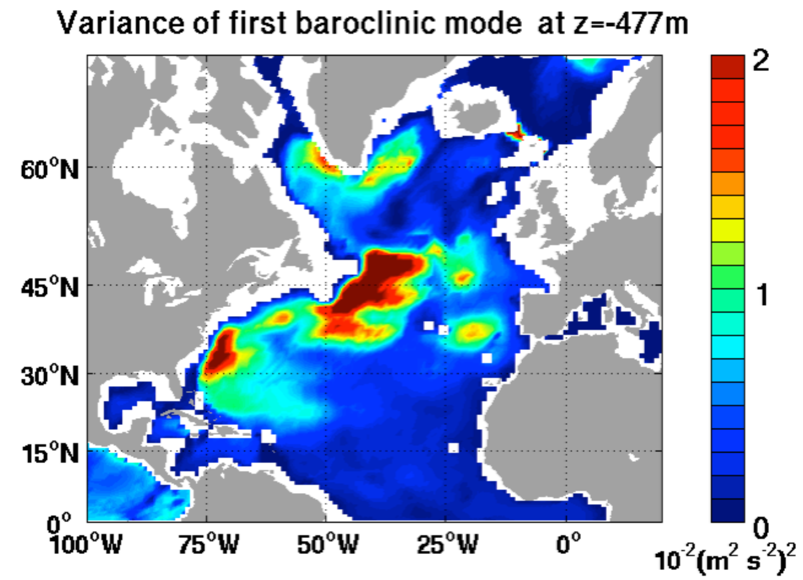
$$\frac{1}{h}\int_{-h}^{0} F_n F_m \, dz = \delta_{nm}$$

$$p = \sum_{n=0}^{\infty} \tilde{p}_n(x,y,t) \; F_n(z)$$

$$\tilde{p}_m(x,y,t) = \frac{1}{h}\int_{-h}^{0} p(x,y,z,t) F_m(z) dz$$

Majority of baroclinic pressure variability in upper ocean is explained by 1st baroclinic mode





Wind Forced Baroclinic Rossby wave model

Horizontal Structure equation for pressure

- **longwave approximation**
- **dominated by 1st baroclinic mode**

➔ **Rossby wave equation for baroclinic pressure (Frankignoul, 1997)**

$$\frac{\partial p_r}{\partial t} + c_r \frac{\partial p_r}{\partial x} = W(x,t) - \epsilon p_r,$$

- $W(x,t) = -\frac{f_o R_1^2}{\rho_o h}\ \mathrm{curl}_z \tau\ F_1(0)$ is the forcing
- c_r is the phase velocity
- ϵ represents the effects of dissipation.

h is the ocean depth

ρ_o is the mean density

f_o is the Coriolis parameter

β is the meridional gradient of f

τ is the surface wind stress

R_1 is the baroclinic Rossby radius.

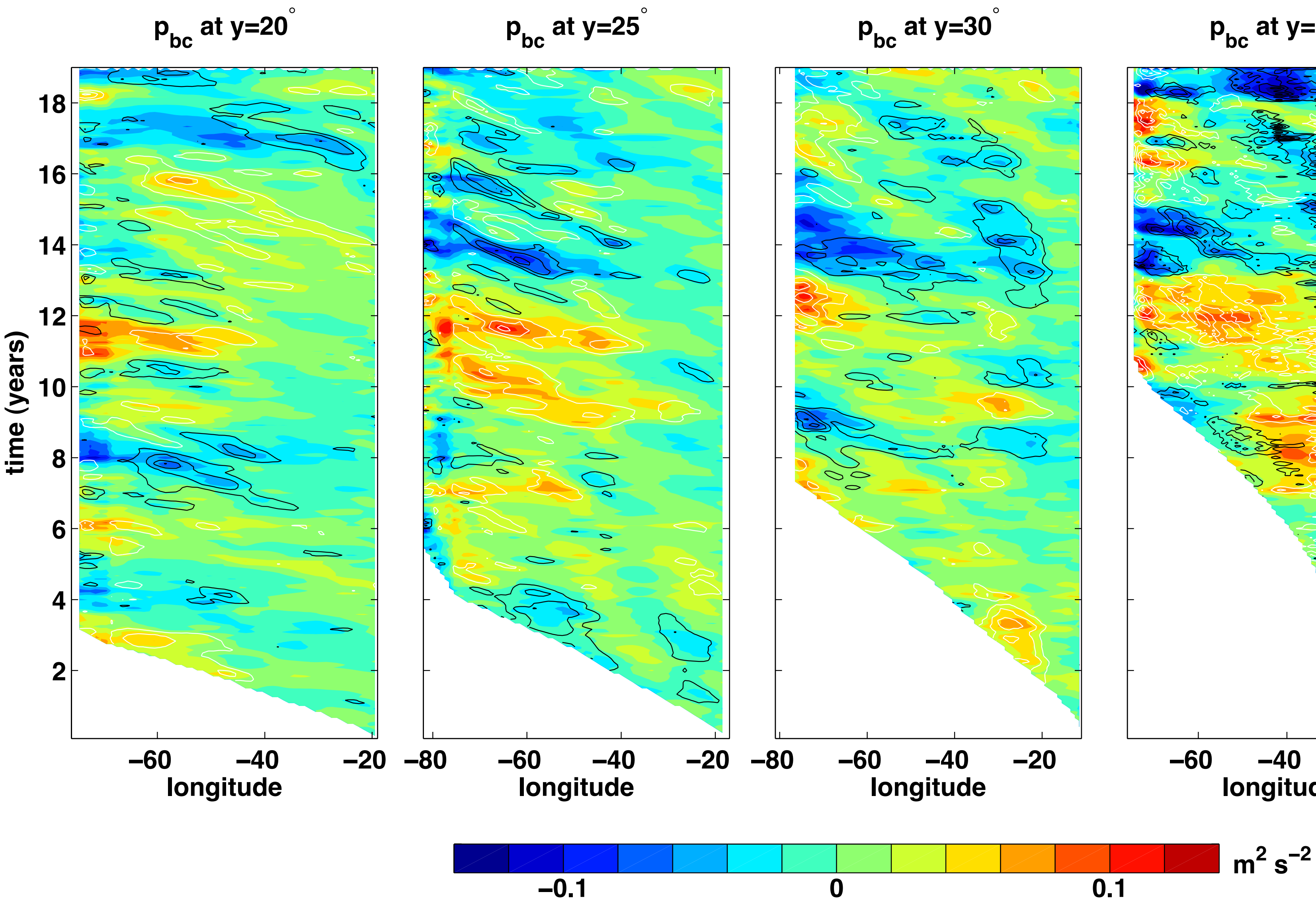
Solve Rossby wave equation via method of characteristics, fitting ε to best match observed p_{bc}.

$$p_r(x,t) = \frac{1}{u(x)}\ p_r\left(x_e, t - \frac{x - x_e}{c_r}\right) + \frac{1}{u(x)} \int_{x_e}^{x} \frac{1}{c_r} W\left(x', t - \frac{x - x'}{c_r}\right) u(x')\ dx', \quad u(x) = \exp \int_{x_e}^{x} \frac{\epsilon}{c_r}\ dx'.$$

↑ **Eastern Boundary Contribution**

↑ **Wind forcing integrated along Rossby wave characteristics**

p_{bc} from ECCO and p_r from Rossby Wave Model

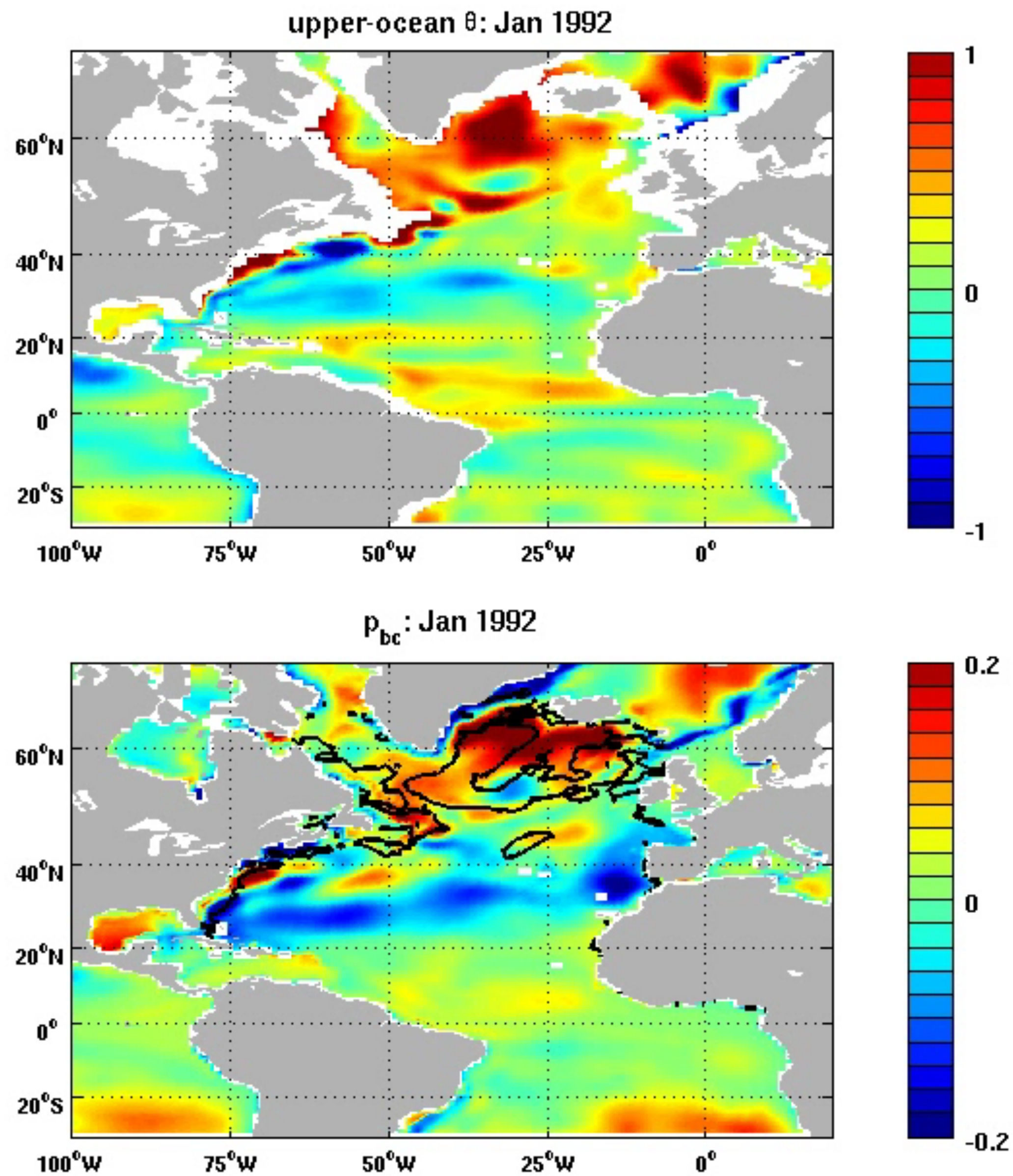


Conclusions

- **Much of the observed upper ocean temperature variability in the interior of the subtropical gyre can be explained as the response of the ocean to atmospheric forcing.**
- **Dynamics of the western boundary current are more complicated.**
- **Subpolar gyre: insufficient data to test Rossby wave model since Rossby waves travel very slowly.**
  - **Local atmospheric forcing may be dominant.**
  - **Convection and non-linearity may play role**
  - **Dynamics of deep western boundary current and AMOC**
- **Upper-ocean temperature anomalies may exist without active participation of AMOC.**
- **Results suggest considering response of ocean to (local and non-local) atmospheric forcing may be useful null hypothesis for evaluating role of AMOC in climate.**

Temperature and baroclinic pressure

- Majority of baroclinic pressure variability in upper ocean is explained by 1st baroclinic mode
- Highly correlated with upper-ocean temperature anomalies (hydrostatic relation).



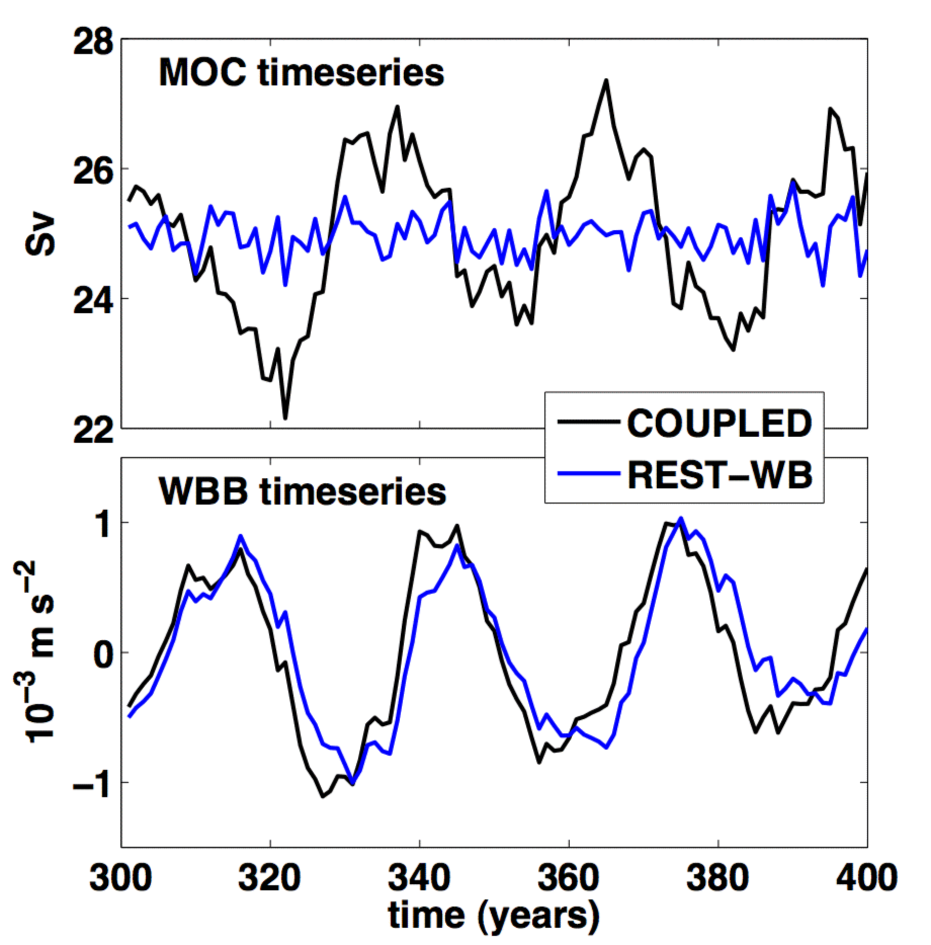
Flat: Role of MOC

Does MOC play a role in creating buoyancy anomalies on WB?

COUPLED

OCEAN-RESTORE WB:

- Initialize w/state from coupled model.
- Force with heat, freshwater, and momentum fluxes from coupled model + restore T,S to climatology along WB south of 50°N on timescale of 1 yr.



Inter-hemispheric MOC variability (on western boundary) does not play a leading order role in creating buoyancy anomalies on the western boundary.