Examining the relationship between low-frequency SST and AMOC variability

Martha W. Buckley and Rui M. Ponte (AER)
Patrick Heimbach and Gaël Forget (MIT)

Observed Atlantic SST anomalies

- **Observations indicate Atlantic SSTs exhibit significant low-frequency variability** (Bjerknes 1964; Kushnir 1994; Ting et al. 2009).
  - e.g. Atlantic Multidecadal Oscillation (Kerr, 2000; Knight et al., 2005)
- **The origin of Atlantic SST anomalies is not fully understood.**
- Likely depends on **timescale**
  - Intra-annual to interannual: response to local atmospheric forcing (Frankignoul and Hasselmann, 1977), e.g. the NAO tripole (Cayan, 1992).
  - Longer timescales (how long?) ocean circulation may play a role.
- **Ocean dynamics that are important have not been isolated**
  - Wind and/or buoyancy forced baroclinic Rossby waves (Sturges and Hong, 1995, 1998; Qiu 2002; Piecuch and Ponte, 2012).
  - Large scale changes in Atlantic ocean heat transport due to changes in the AMOC (Kushnir 1994, etc.) and gyre circulations.
  - Lozier (2010): most significant question concerning the AMOC is (potential) role of AMOC in creating decadal SST anomalies.

Approach

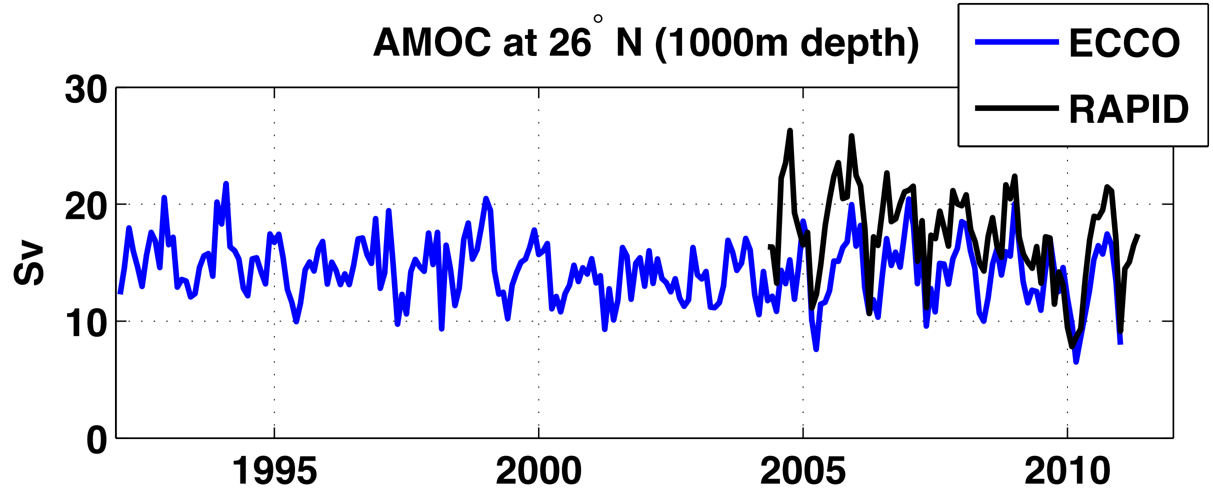
What are relative roles of local atmospheric forcing and ocean dynamics in upper-ocean heat content (UOHC) variability in the North Atlantic?

- ➢ Does the AMOC play an active role in creating UOHC anomalies?

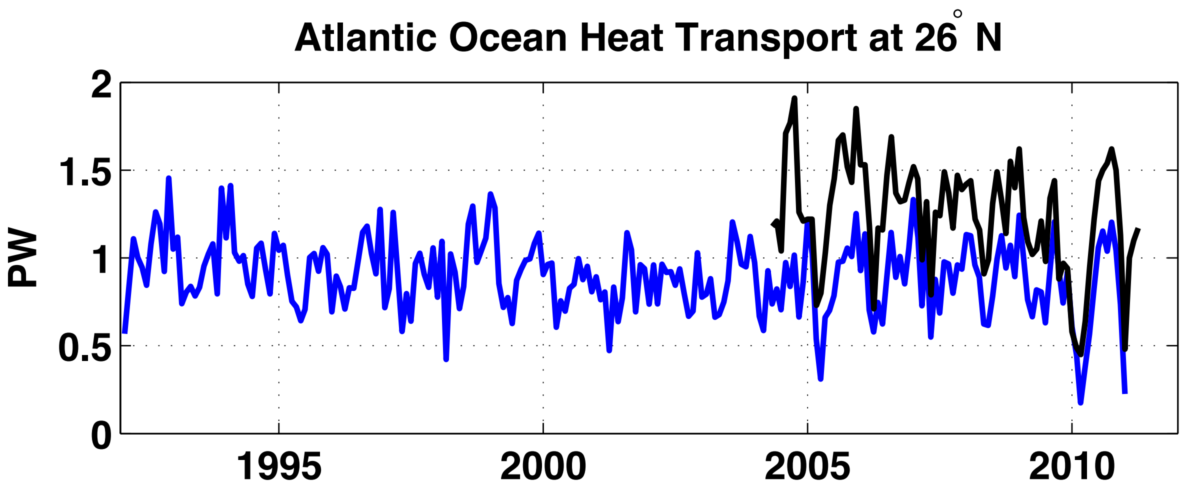
Method: ECCO version 4 state estimate (1992-2010)

- MITgcm least squares fit to observations using adjoint (Wunsch et al., 2009)
- fit achieved by adjusting initial conditions, forcing, and model parameters
- satisfies equations of motion & preserves property budgets (Wunsch & Heimbach, 2013)
- Atmospheric forcing: ERA-Interim
- Ocean data:
  - In-situ: Argo, CTDs, XBTs, mooring arrays
  - AVHRR & AMSR-E SST and satellite altimetry
- Model details (G. Forget)
  - New global grid (LLC90), includes Arctic, 50 vertical levels, partial cells
  - Nominal 1° resolution with telescopic resolution to $1/3^{\circ}$ near Equator
  - State of the art dynamic/thermodynamics sea ice model
- Fit to observations achieved by optimization—see poster, Forget et al, in prep.

Monthly AMOC and Atlantic OHT variability



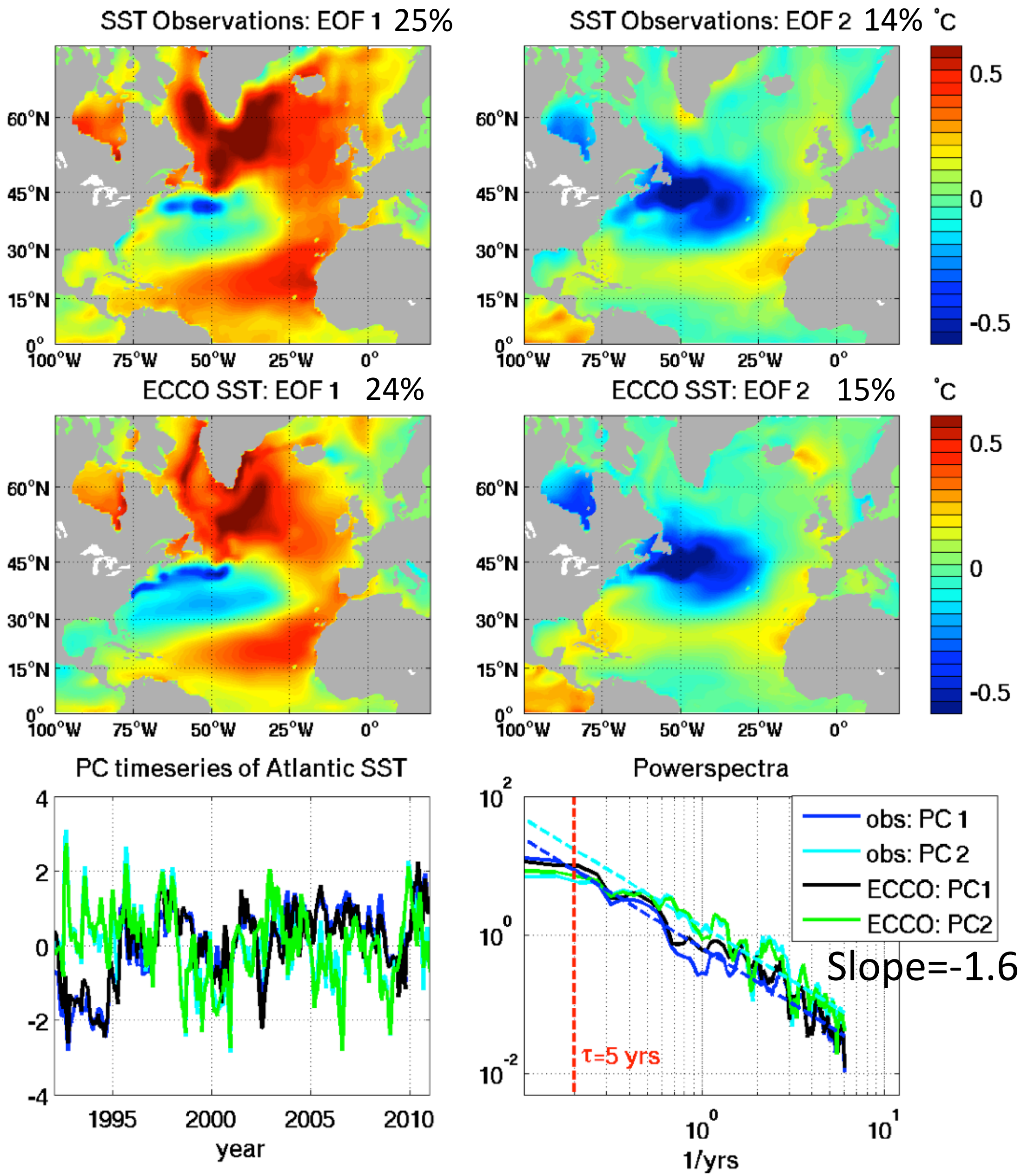
- Mean
  - ECCO: 16.0 Sv
  - RAPID: 17.5 Sv
- Correlation 0.75
- improves w/ time



- Means
  - ECCO: 0.86 PW
  - RAPID: 1.2 PW
- ECCO systematically underestimates OHT
- Correlation: 0.81

Note: Neither Florida current transports (cable observations) or RAPID AMOC transport estimates at 26ºN are used as constraints in ECCO

Low-frequency Atlantic SST variability



- Analysis of monthly data, seasonal cycle removed
- Atlantic SST variability in ECCO similar to Reynolds (2002) gridded SST.
- Pattern resembles classic "NAO tripole"
- Spectrum is red: slope=-1.6

What are roles of:

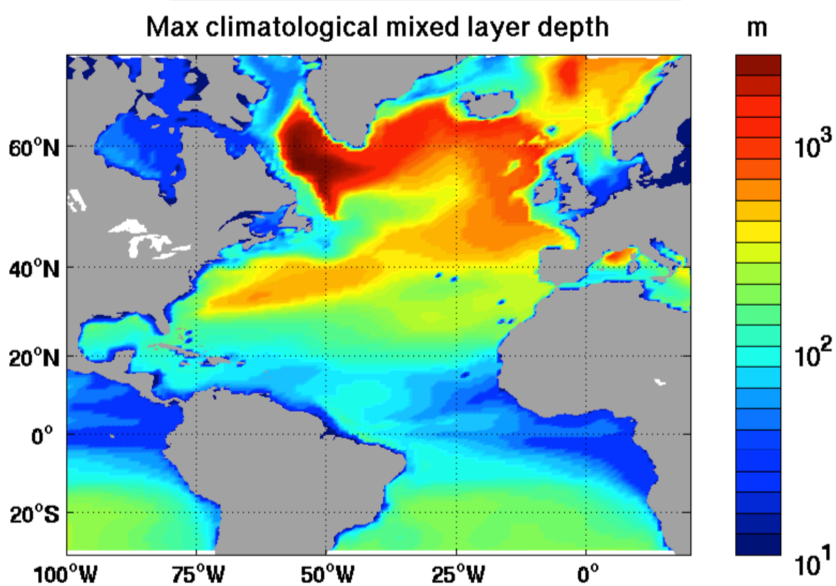
- **local atmospheric forcing**
  - Air-sea heat fluxes
  - Ekman transports
- **versus ocean dynamics?**
  - Rossby waves
  - Changes in gyre circulations and AMOC

Upper ocean heat content variability

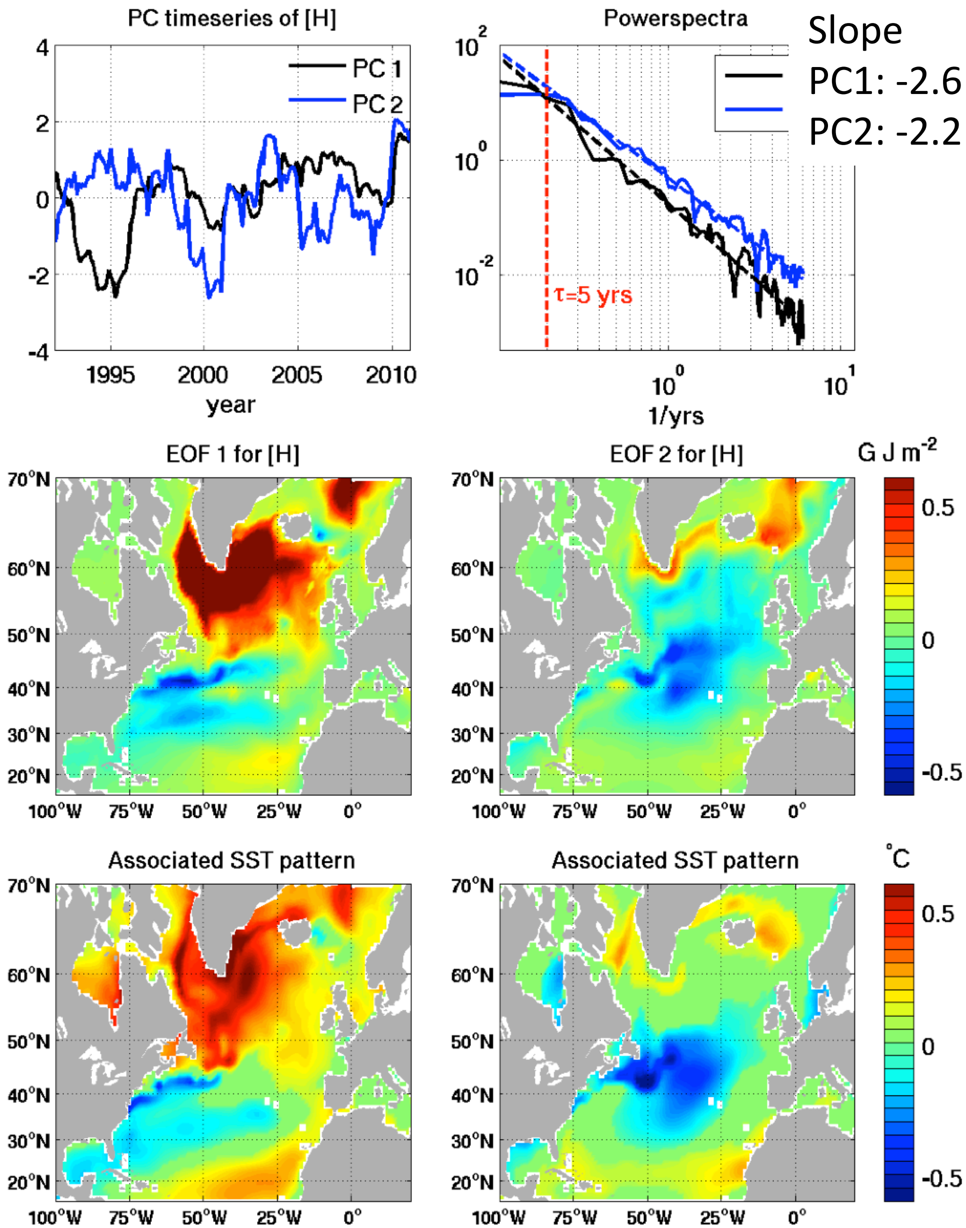
Heat Content integrated over max. climatological mixed layer depth

- Measure of heat contained in "active" ocean layers
- Implicitly accounts for re-emergence of SST anomalies (Deser et al, 2003; Coetlogon and Frankignoul, 2003)

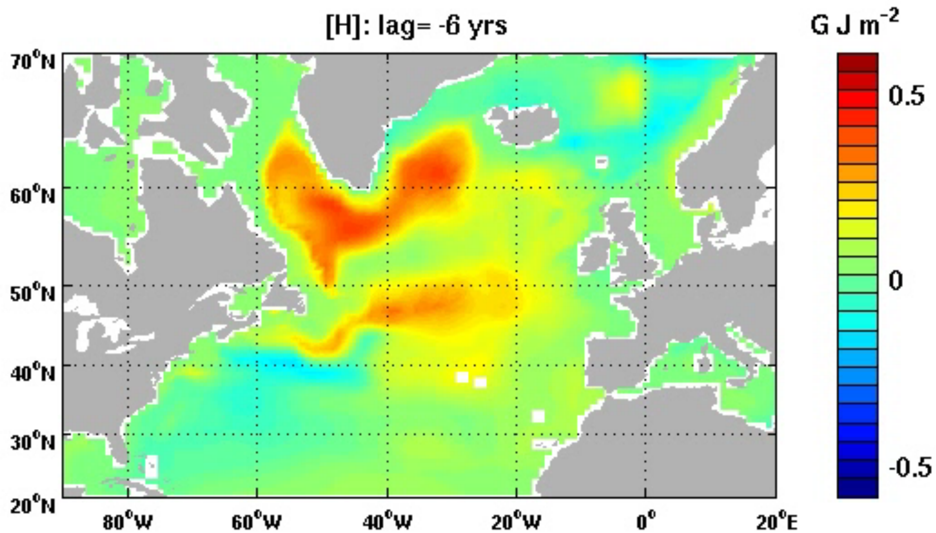
$$H = \rho_o C_p \int_{-D}^{\eta} T \, dz$$

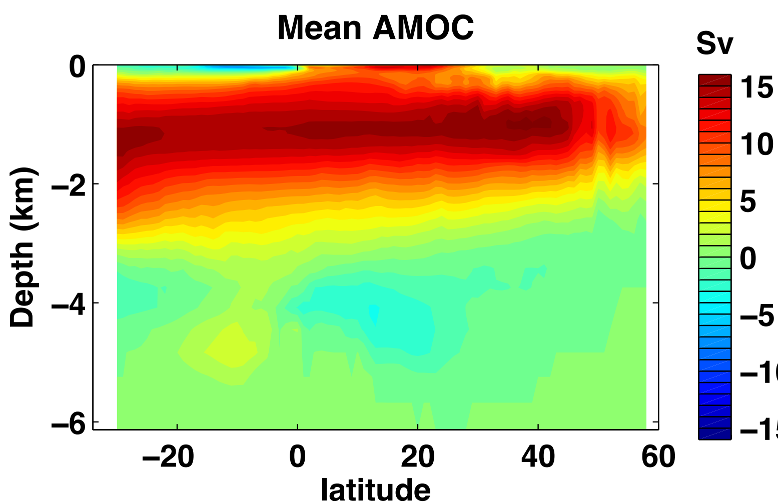


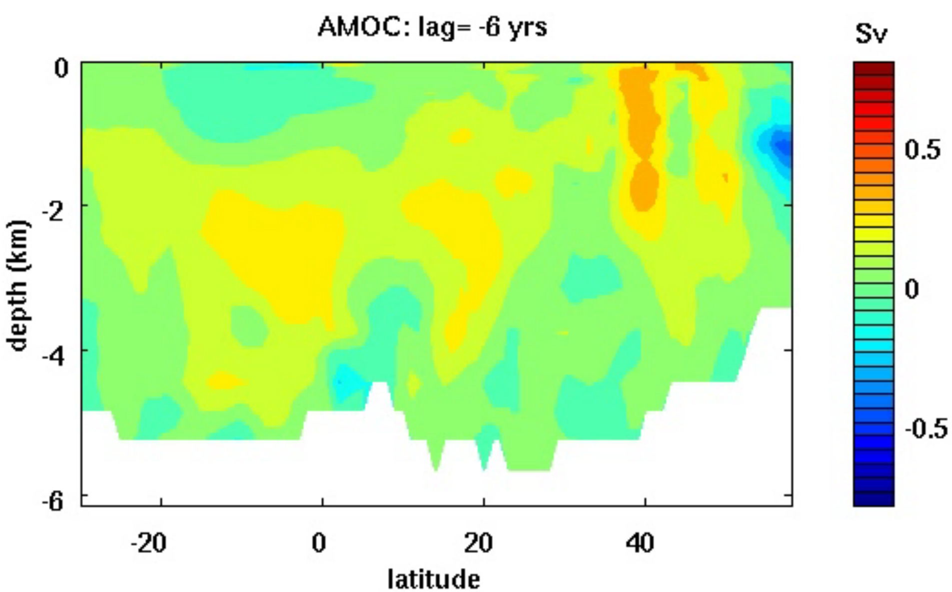
Slope
PC1: -2.6
PC2: -2.2



Relationship to AMOC variability



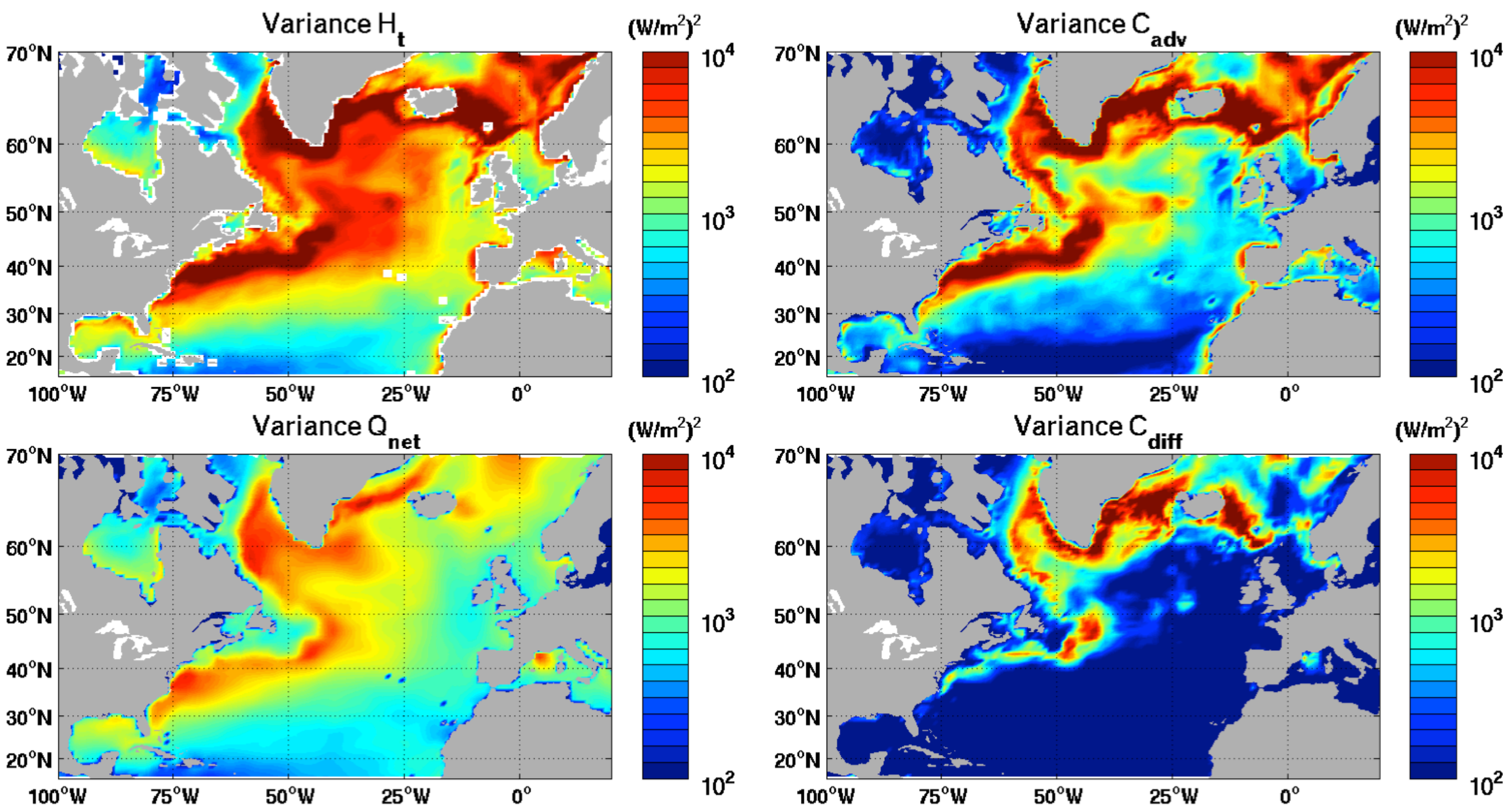




- H variability is associated with AMOC variability. Is AMOC variability passive thermal wind response to H variability or does AMOC play role in H budget in some regions (e.g. Gulf Stream)?

Upper ocean heat content budget

$$\rho_o C_p \int_{-D}^{\eta} \frac{\partial T}{\partial t}\,dz = \underbrace{-\rho_o C_p \int_{-D}^{\eta} \nabla \cdot (\mathbf{u}T + \mathbf{u}^* T)\,dz}_{C_{adv}} - \underbrace{\rho_o C_p \int_{-D}^{\eta} \nabla \cdot \mathbf{K}\,dz}_{C_{diff}} + Q_{net}$$



Advection is important in creating H_t variability along the Gulf Stream Path and in regions in the subpolar gyre

Origin of advective heat transport convergence

Linear, Ekman, and geostrophic convergences

$$C_{adv} = \underbrace{-\rho_o C_p \int_{-D}^{\eta} \nabla\cdot(\bar{\mathbf{u}}\bar{T})\,dz}_{\text{linear: } C_{lin}} \underbrace{-\rho_o C_p \int_{-D}^{\eta} \nabla\cdot(\overline{\mathbf{u}'T'} + \overline{\mathbf{u}^* T})\,dz}_{\text{bolus: } C_{bol}}$$

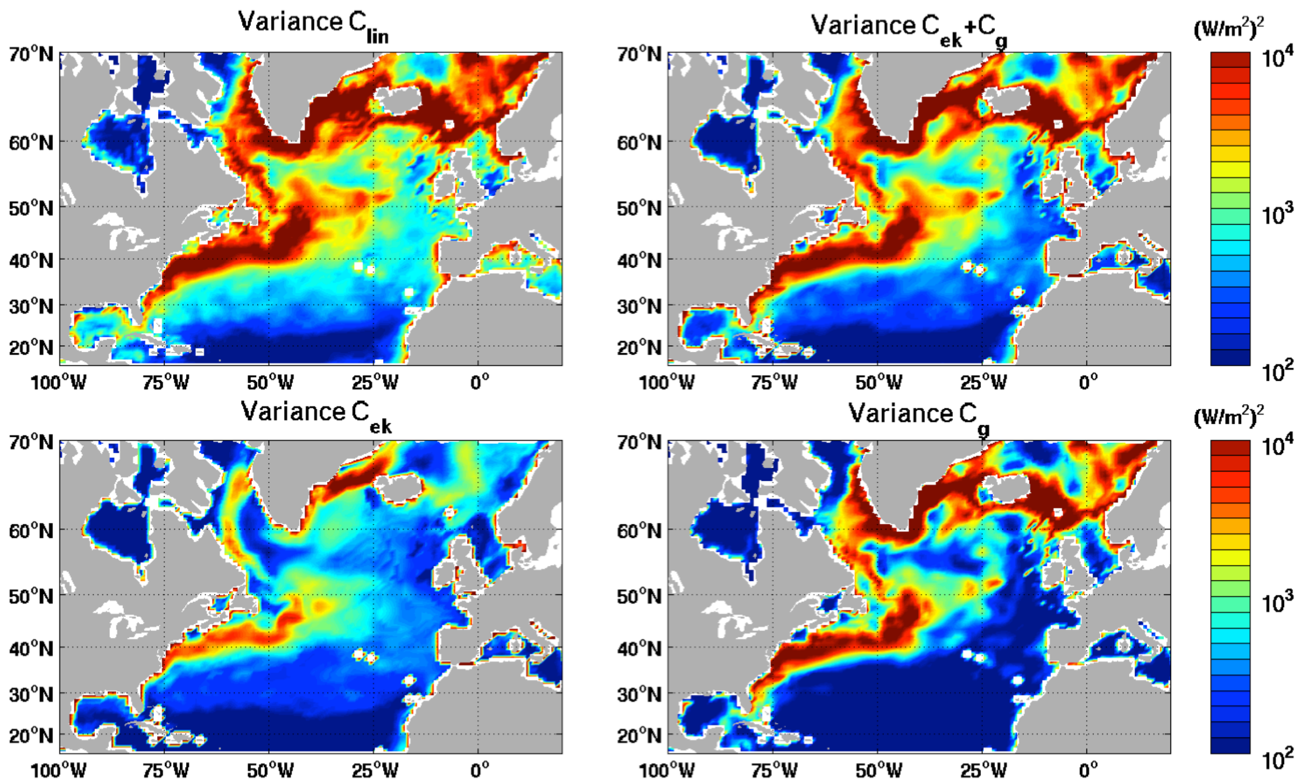
$$C_{ek} = \rho_o C_p \int_{-D_{ek}}^{\eta} \nabla\cdot(\bar{\mathbf{u}}_{\mathbf{ek}}\bar{T})\,dz + \rho_o C_p\ \overline{w}_{ek}(-D)\ \overline{T}(-D)$$

$$C_g = \rho_o C_p \int_{-D}^{\eta} \nabla\cdot(\bar{\mathbf{u}}_{\mathbf{g}}\bar{T})\,dz + \rho_o C_p\ \overline{w}_g(-D)\ \overline{T}(-D)$$

$$\mathbf{u_g} = \frac{1}{f\rho_o}\hat{\mathbf{z}}\times\nabla p,$$

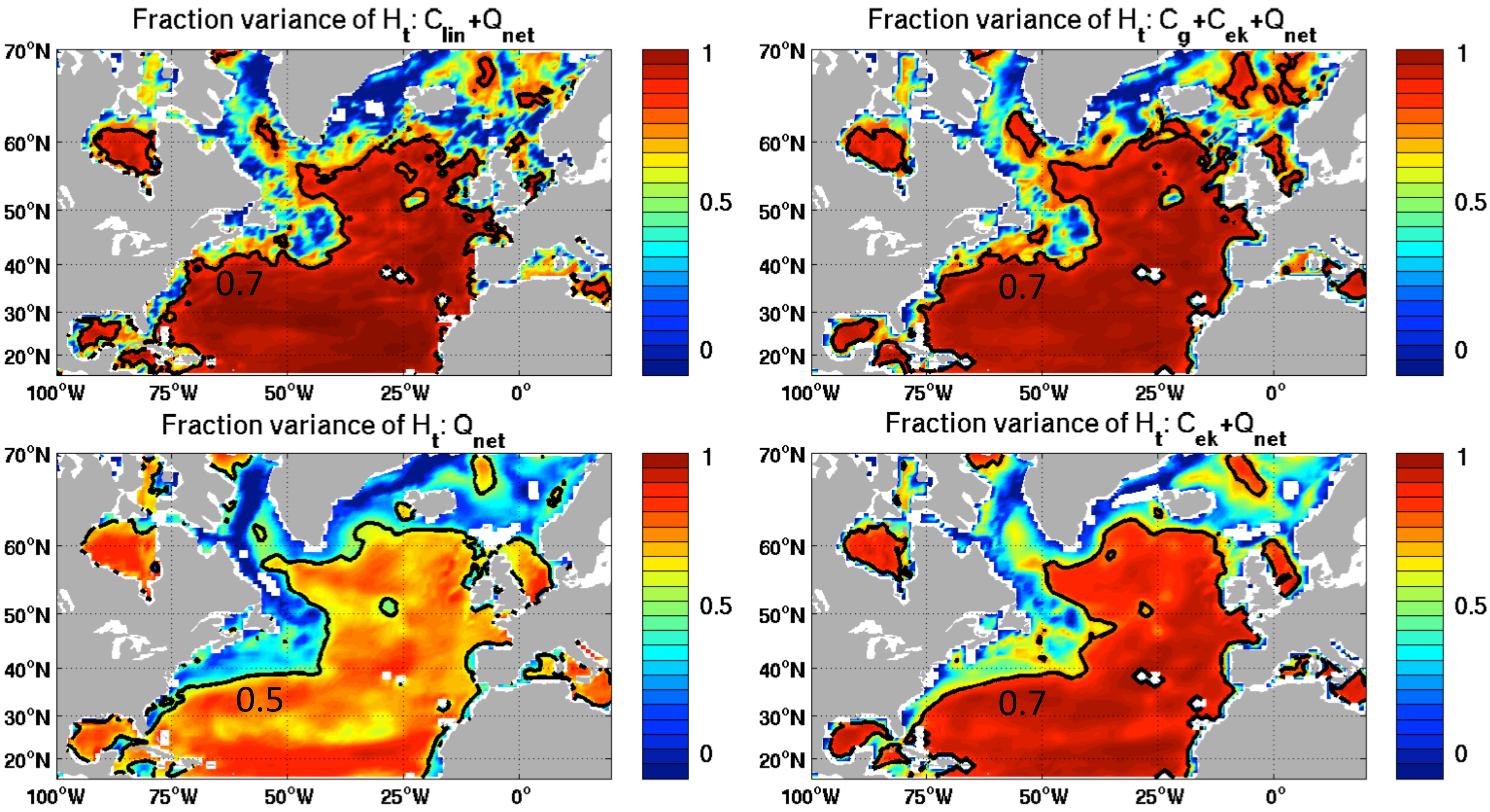
$$\mathbf{u_{ek}} = \frac{\tau\times\hat{\mathbf{z}}}{\rho_o f D_{ek}},\quad D_{ek} = \min(D, 100\ \mathrm{m})$$

$$w(-D) \approx \int_{-D}^{\eta}\nabla_H\cdot\mathbf{u}\,dz \approx \underbrace{\int_{-D_{ek}}^{\eta}\nabla_H\cdot\mathbf{u_{ek}}\,dz}_{\equiv w_{ek}(-D)} + \underbrace{\int_{-D}^{\eta}\nabla_H\cdot\mathbf{u_g}\,dz}_{\equiv w_g(-D)}$$



- C_{adv} is well reproduced by C_{lin} in most regions
- $C_{ek}+C_g \approx C_{lin}$
- Both C_{ek} and C_g largest in regions of strong currents/fronts
- C_{ek} also significant over gyre interiors

Role of Local Air-Sea Heat Flux + Ekman forcing

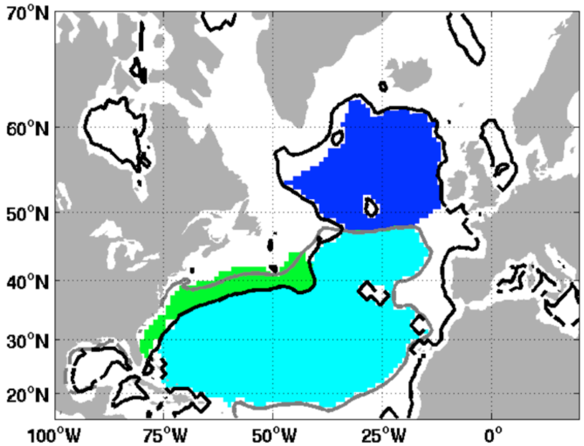


$$F(A,B) = 1 - \frac{var(A-B)}{var(A)}$$

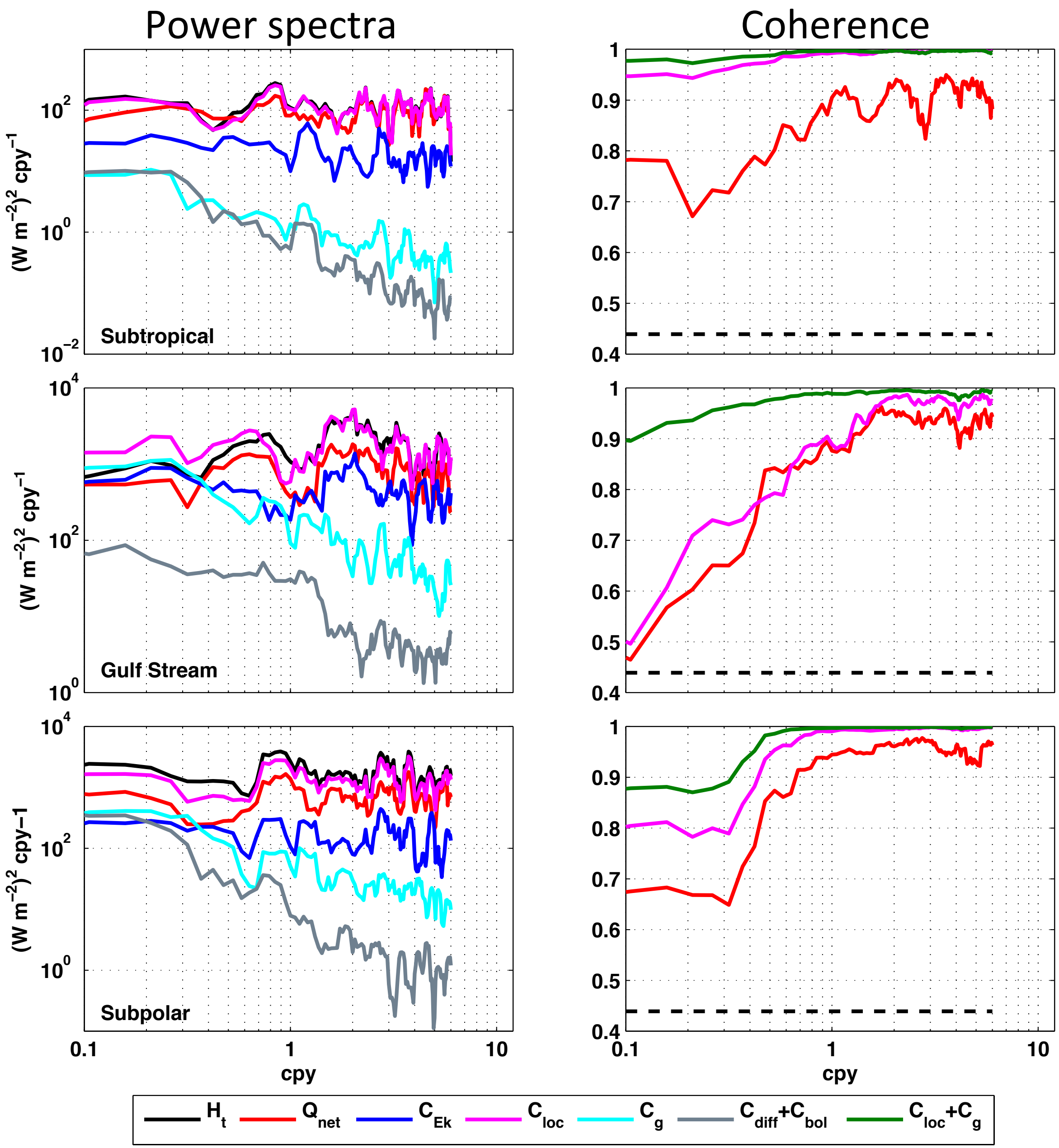
- Local Atmospheric Forcing explains >70% of variance of H_t in interior of the subtropical and subpolar gyres.
- Geostrophic convergence important along Gulf Stream path.

Regional budgets: fluxes

Divide into regions based on dynamics

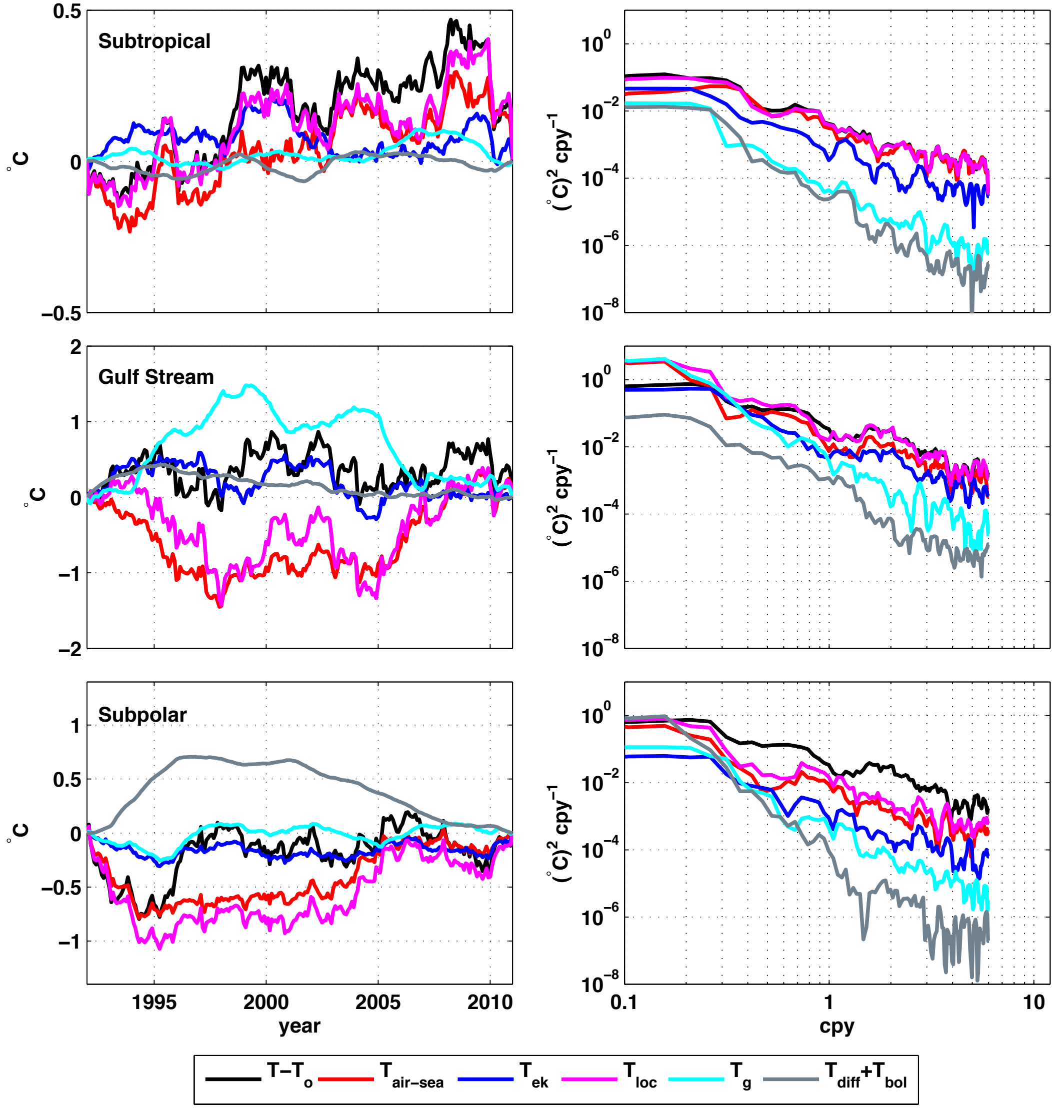


1) Subtropical gyre
   - C_{loc} dominates on all timescales
2) Gulf Stream
   - C_{loc} dominates for τ<6 mo
   - C_g increasing role on longer timescales
3) Subpolar gyre
   - C_{loc} Dominates for τ< 1 yr
   - C_g , C_{diff}, C_{bol} all play a role for τ> 1 year



Regional budgets: time integrated

$$\underbrace{\int_0^t \frac{H_t}{\rho_o C_p V}\, dt}_{\equiv (T-T_o)} = \underbrace{\int_0^t \frac{C_{adv}}{\rho_o C_p V}\, dt}_{\equiv T_{adv}} + \underbrace{\int_0^t \frac{C_{diff}}{\rho_o C_p V}\, dt}_{\equiv T_{diff}} + \underbrace{\int_0^t \frac{Q_{net}}{\rho_o C_p V}\, dt}_{\equiv T_{air-sea}} .$$



1) Subtropical gyre
   - T_{loc} explains 91% of the variance of T-T_o

2) Gulf Stream
   - T_g important in T-T_o budget
   - T_g and $T_{air\text{-}sea}$ highly anticorrelated (-0.90)

3) Subpolar gyre
   - T_{diff} and T_{bol} also contribute to T-T_o budget

Conclusions

- Heat content integrated over the climatological mixed layer depth H is a useful measure of the ocean's upper-ocean heat content.
- Both advection and air-sea heat fluxes play a role in variability in H_t, the tendency of H.
- Method of approximating the advective heat transport convergence as the sum of the Ekman and geostrophic transports is successful over most of subtropical and subpolar gyres.
    - Exceptions: boundary regions of subpolar gyre, Mann Eddy region, region near Gulf Stream separation
- Over the interior of the subtropical and subpolar gyres >70% of the variance of H_t can be explained by local air-sea heat flux + Ekman transport variability.
- Geostrophic convergence plays a role along Gulf Stream Path.

Preliminary Conclusions (cont.)

- Importance of various terms in variance of H_t depends on timescale (see poster)
  - Subtropical gyre: local forcing dominates on all timescales.
  - Gulf Stream: local forcing dominates for periods less than 6 months; geostrophic convergences increasingly important on longer timescales.
  - Subpolar gyre: local forcing dominates for periods less than 1 year; geostrophic transports, bolus transports, and diffusion play a role on longer timescales.
- Temporally integrated budgets emphasize terms important in H variability
  - Subtropical gyre: majority of H variance explained by local forcing
  - Gulf Stream region: geostrophic transports also important, anticorrelated with air-sea heat fluxes, suggesting H variability is forced by geostrophic convergences and damped by air-sea fluxes.
  - Subpolar gyre: diffusion and bolus transports also important

Future work

- Determine origin of geostrophic convergence anomalies over the Gulf Stream path
  - Shift of Gulf Stream path due to remote wind forcing?
  - Change in strength of deep western boundary current?

- Better understand origin of low-frequency variability of diffusion and bolus transports in the subpolar gyre—appear to be related to low-frequency variability of wintertime mixed layer depths.

- H variability is associated with AMOC variability. Is AMOC variability passive thermal wind response to H variability or does AMOC play role in H budget in some regions (e.g. Gulf Stream)?

- Analysis has isolated regions where more complex dynamics are important in H budgets—e.g. diffusion and bolus transports are important in Mann Eddy region. Explore dynamics of these regions.