The Contributions of Ekman Heat Advection to Meridional Heat Transport Anomalies in the Atlantic Ocean

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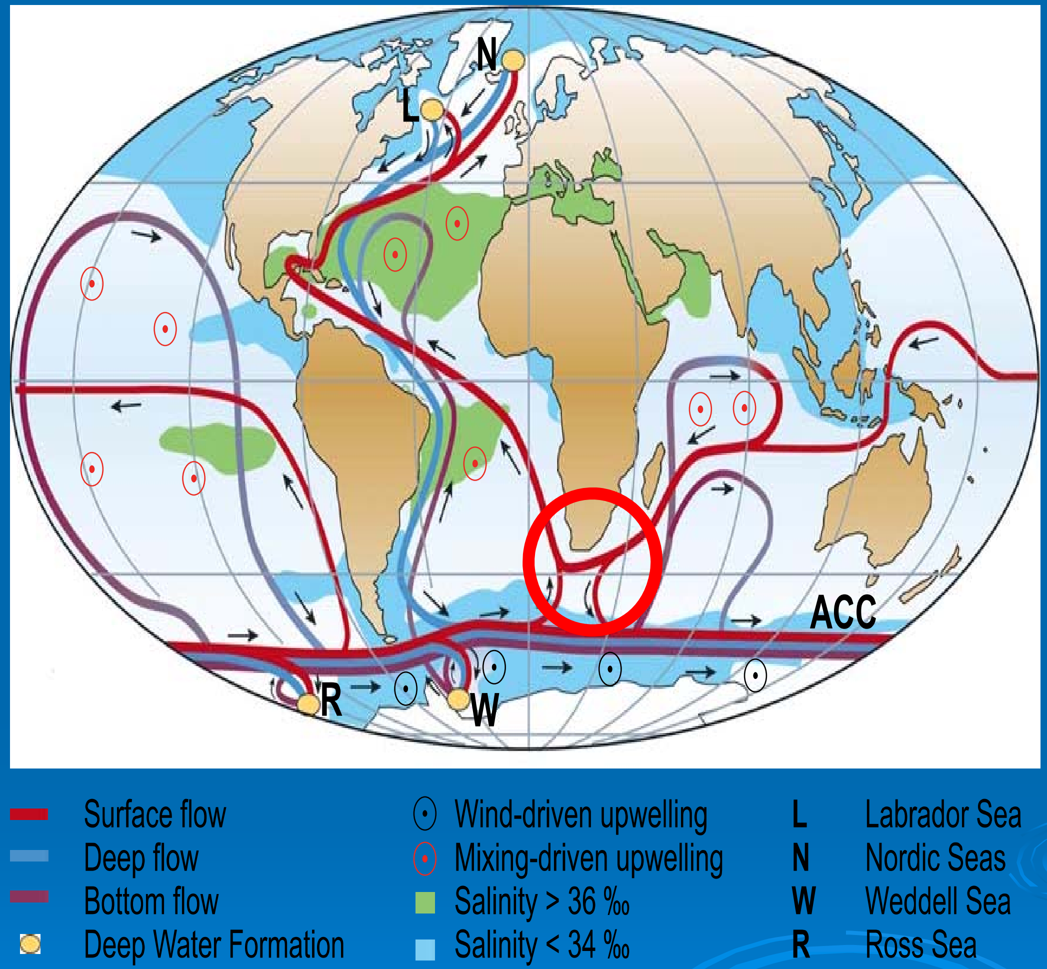
Heat Transport in the Atlantic

- Ocean heat conveyor
- Convergence from Indian and Pacific Oceans
- Northward in Atlantic
- Heat loss over boundary currents



Kuhlbrodt et al. (2007)

Outline

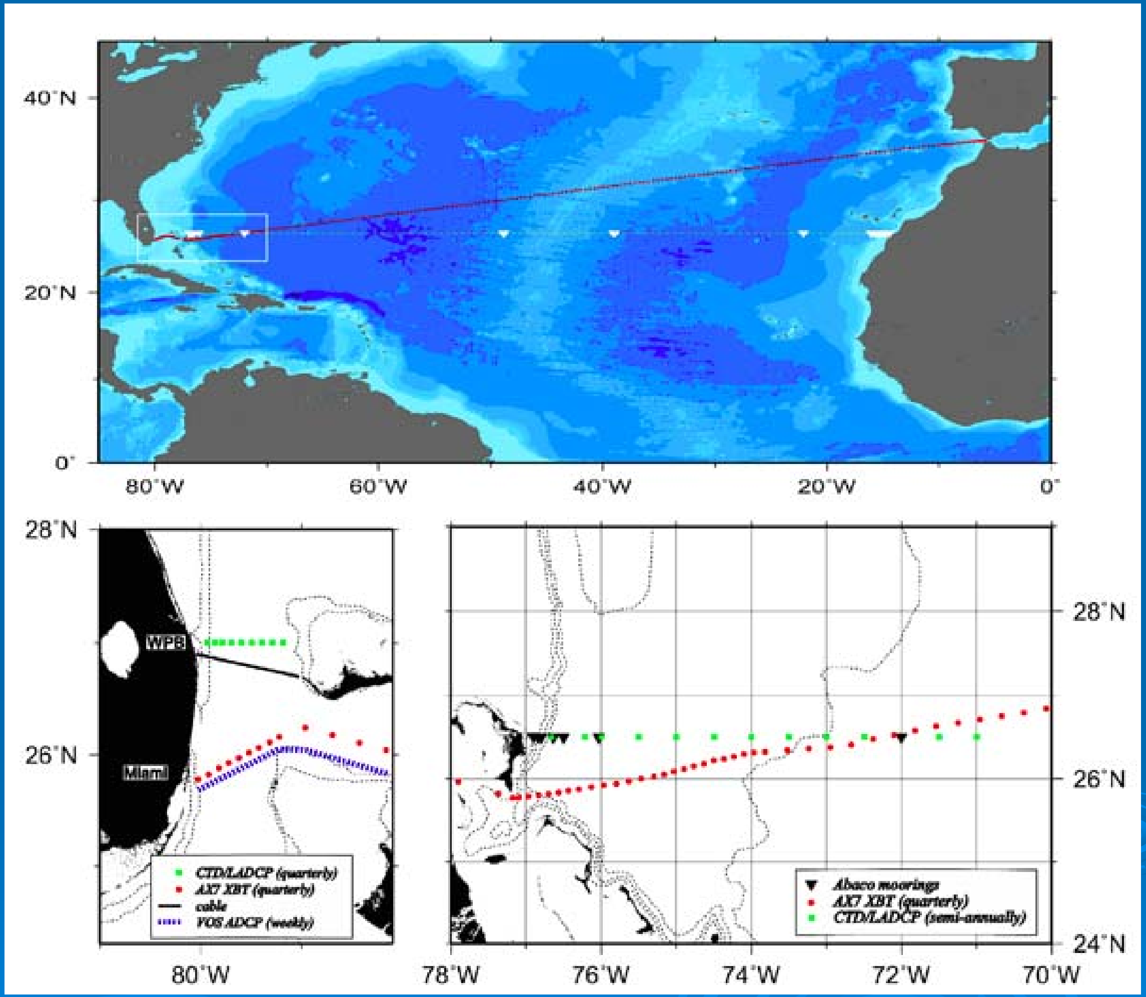
- Inferring MHT from heat budget
- Variability and forcing of MHT
- Contributions of Ekman advection
- Role of the South Atlantic or Agulhas

RAPID/MOCHA Array

Direct measurements of AMOC and MHT in subtropical North Atlantic (UK and US)

Moored current meters & sensors, hydrographic surveys and monitoring of Florida Current (Gulf Stream)

Since April 2004



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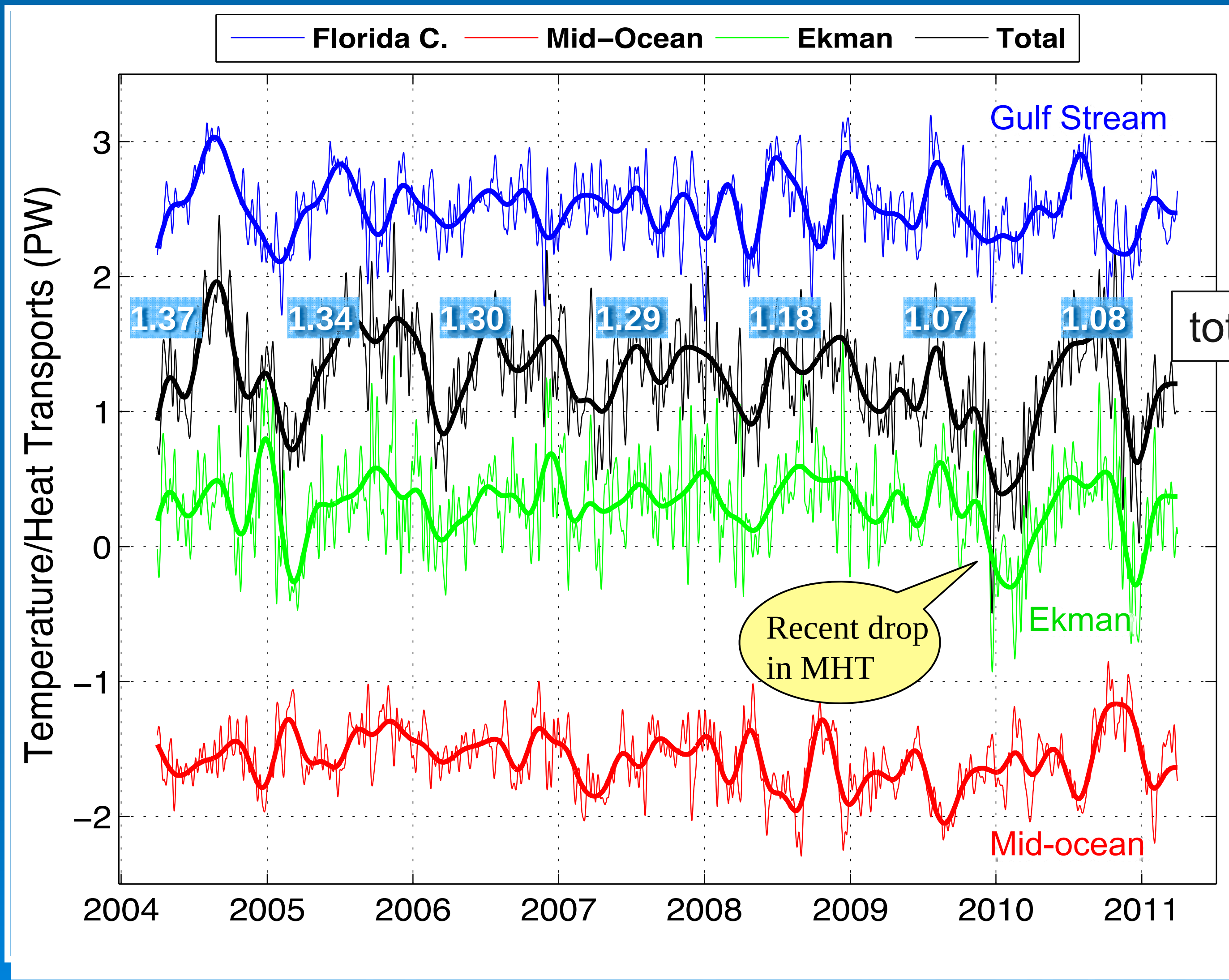
Contributions to MHT at 26.5ºN

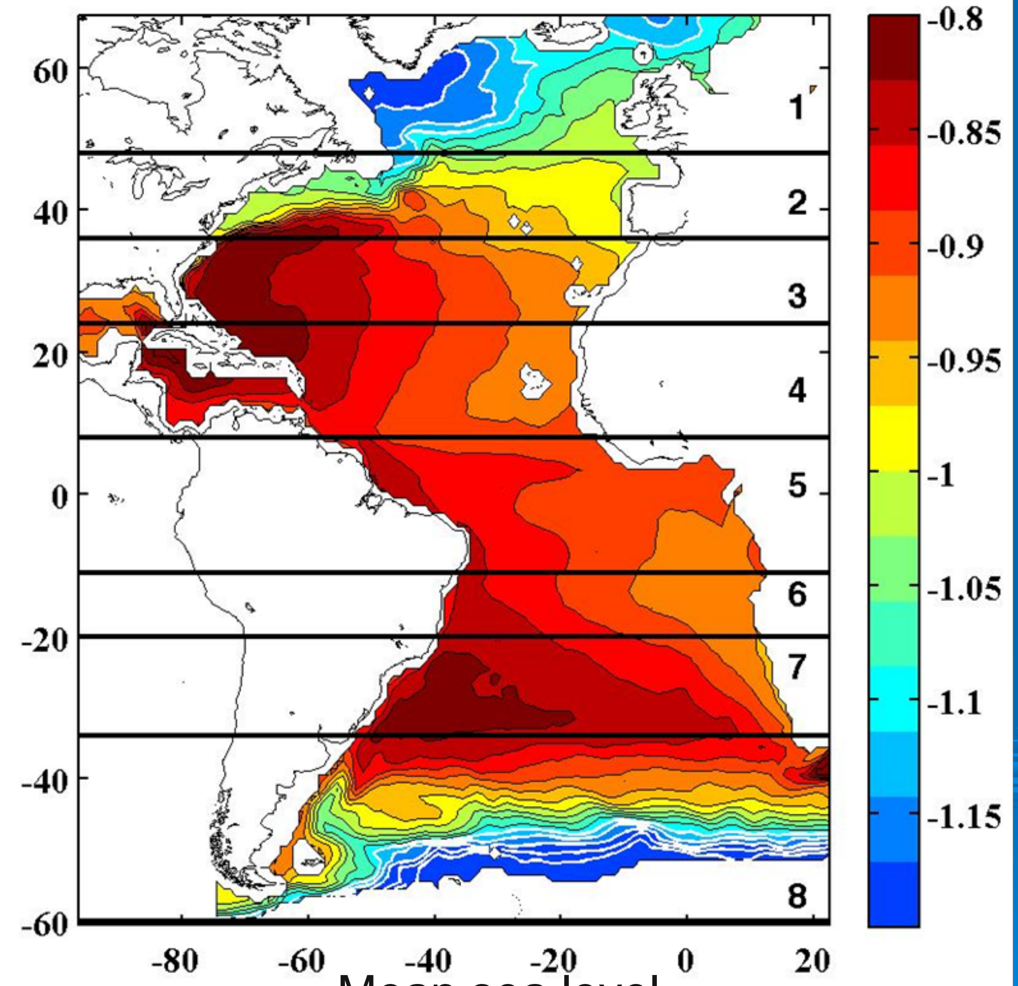


2004-2011 mean heat transport: 1.25 PW

courtesy W. Johns

Estimate MHT for Entire Atlantic: 1993-2010

- 8 regions (boxes)
- Simple box model
- Infer MHT anomalies from heat budget



Mean sea level

Use SSH for Heat Content?

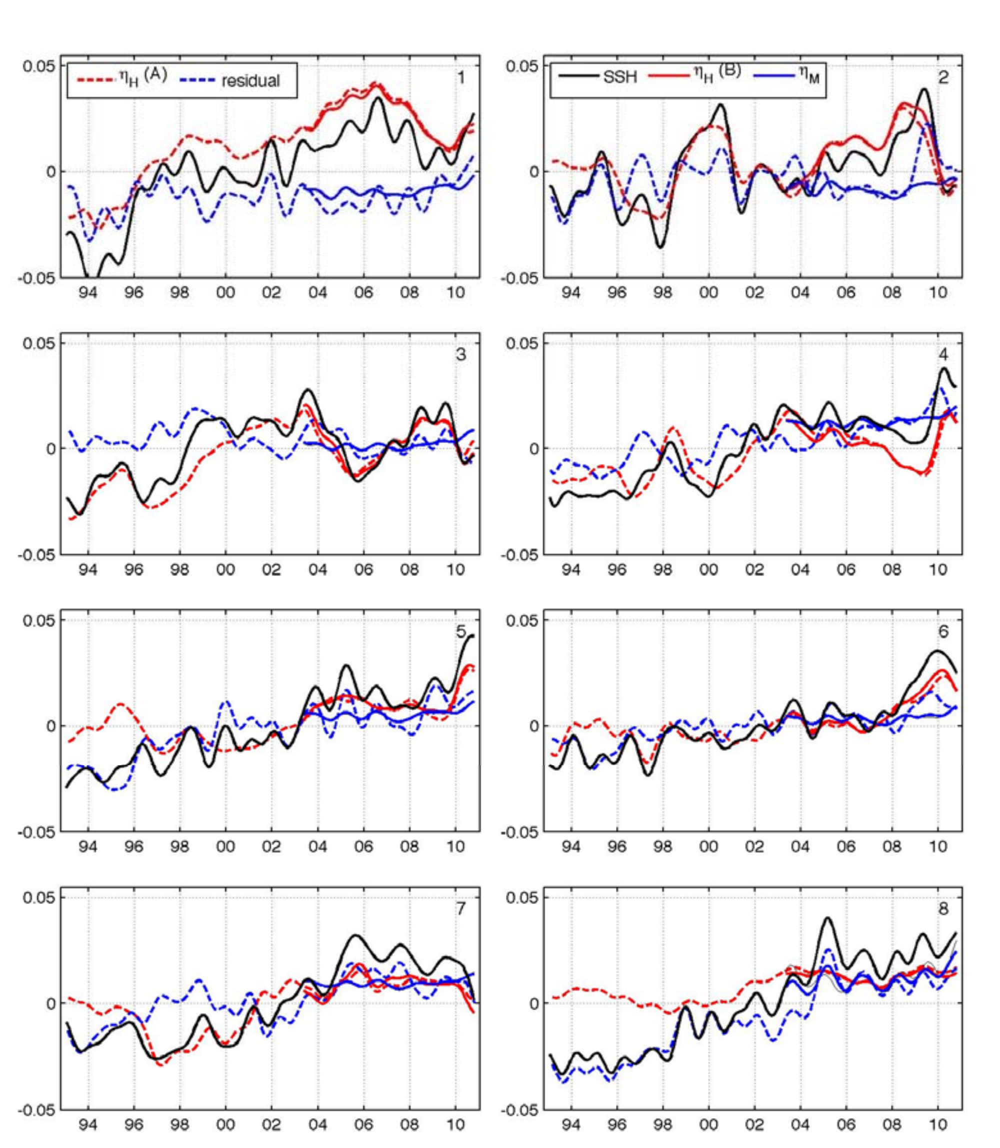
- Thermosteric sea level: poor resolution & coverage
- Budget including TSL, SSH and GRACE EWT

  ⇨ heat dominates over mass and salt

  thermosteric

  altimetric sea level

  mass + salt



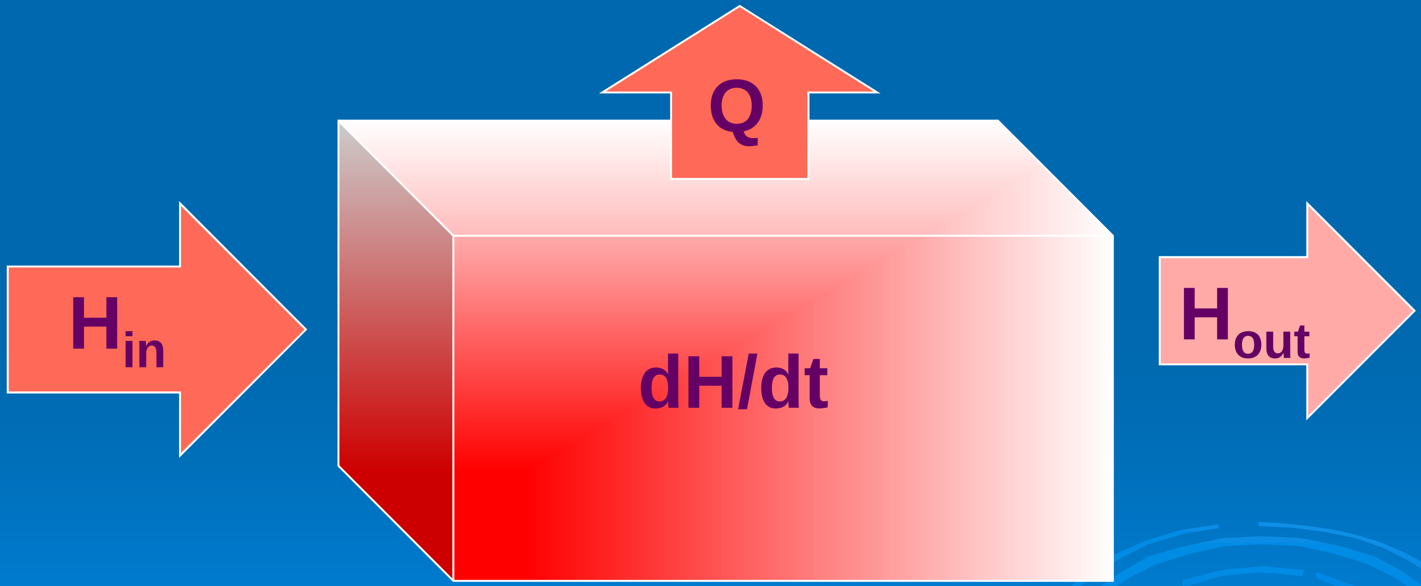
Estimate Heat Transport Convergence

Components of the heat budget:

Surface heat flux Q

Heat storage rate dH/dt

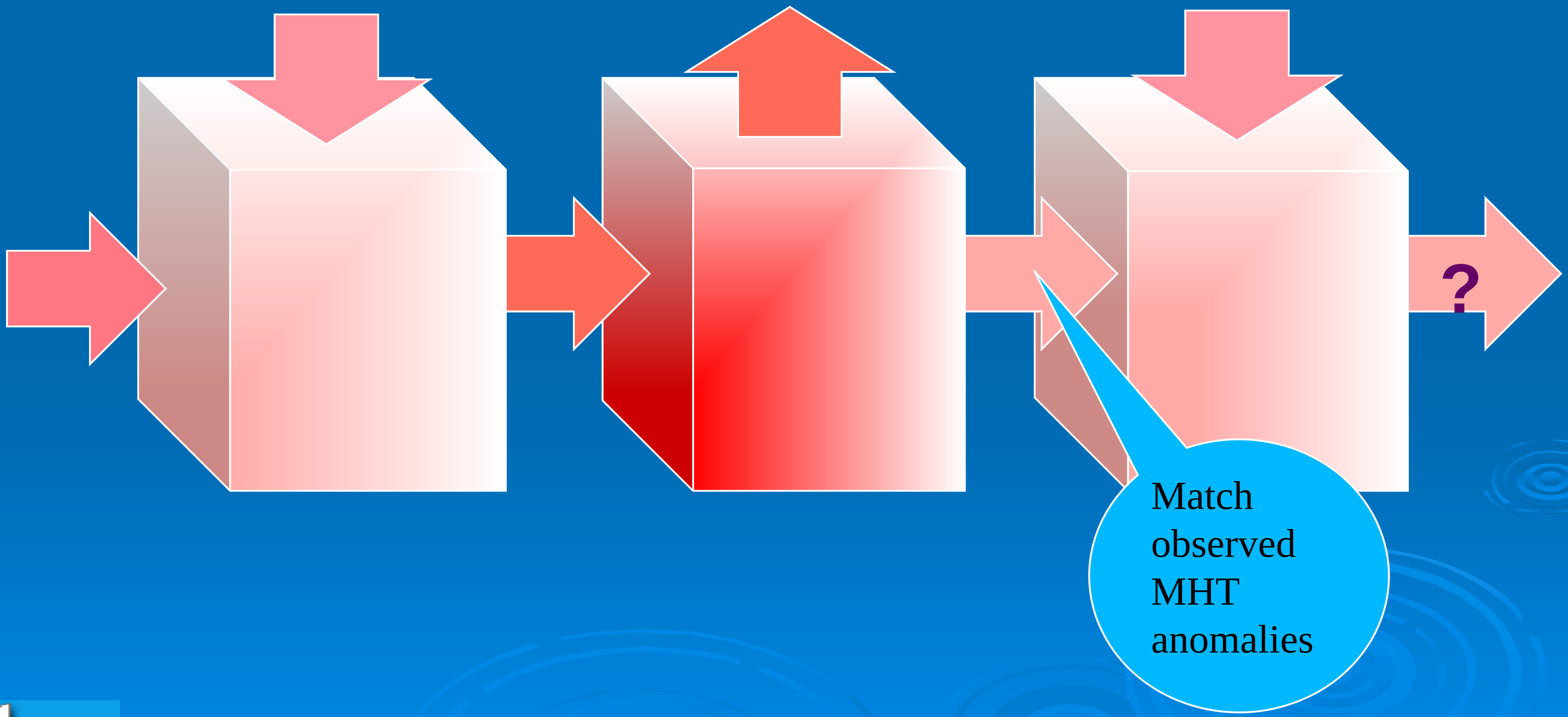
Heat transport convergence (HTC): H_{in} - H_{out}



Sum HTC for Meridional Heat Transport

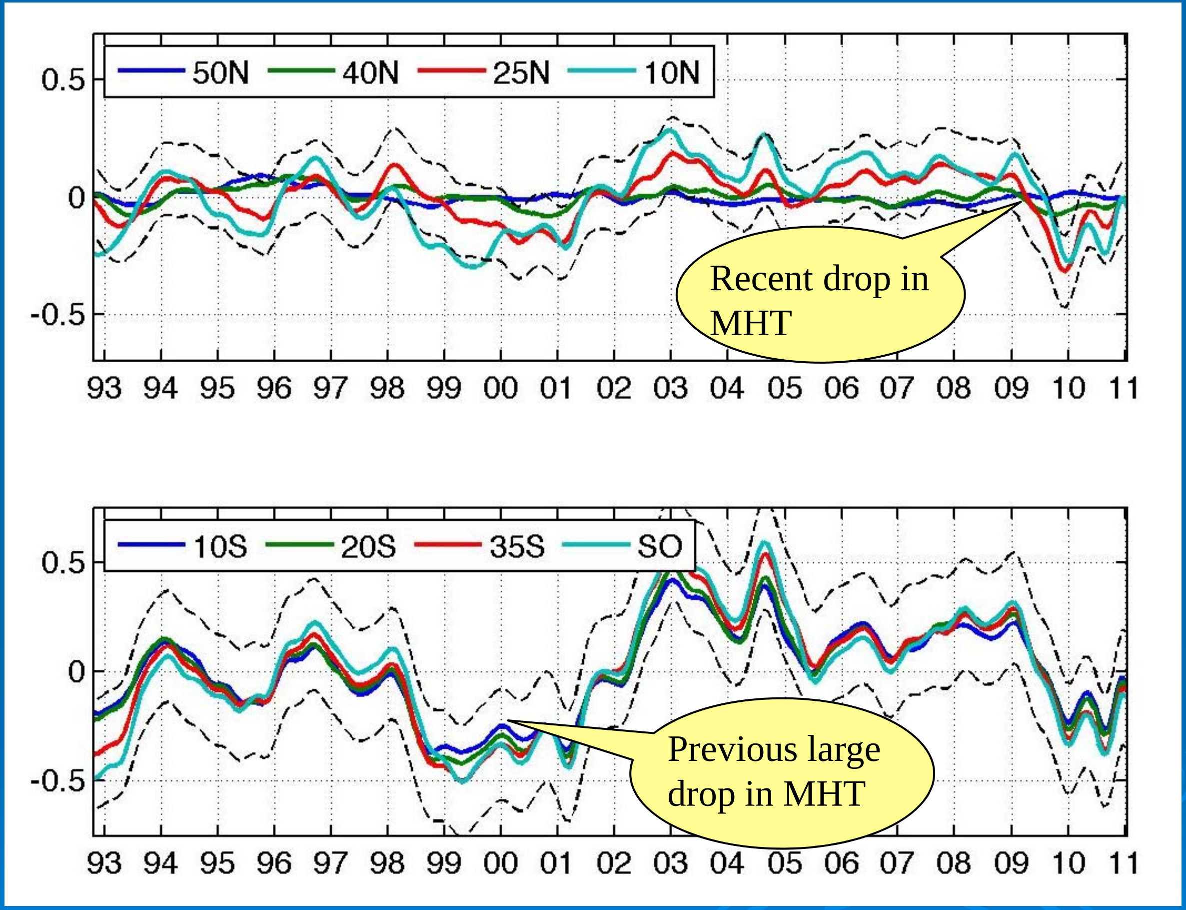
Use HTC to get MHT:

- sum HTC starting from northern box
- match observed anomalies at 40N (*Willis 2004*)



MHT Anomalies Using SSH

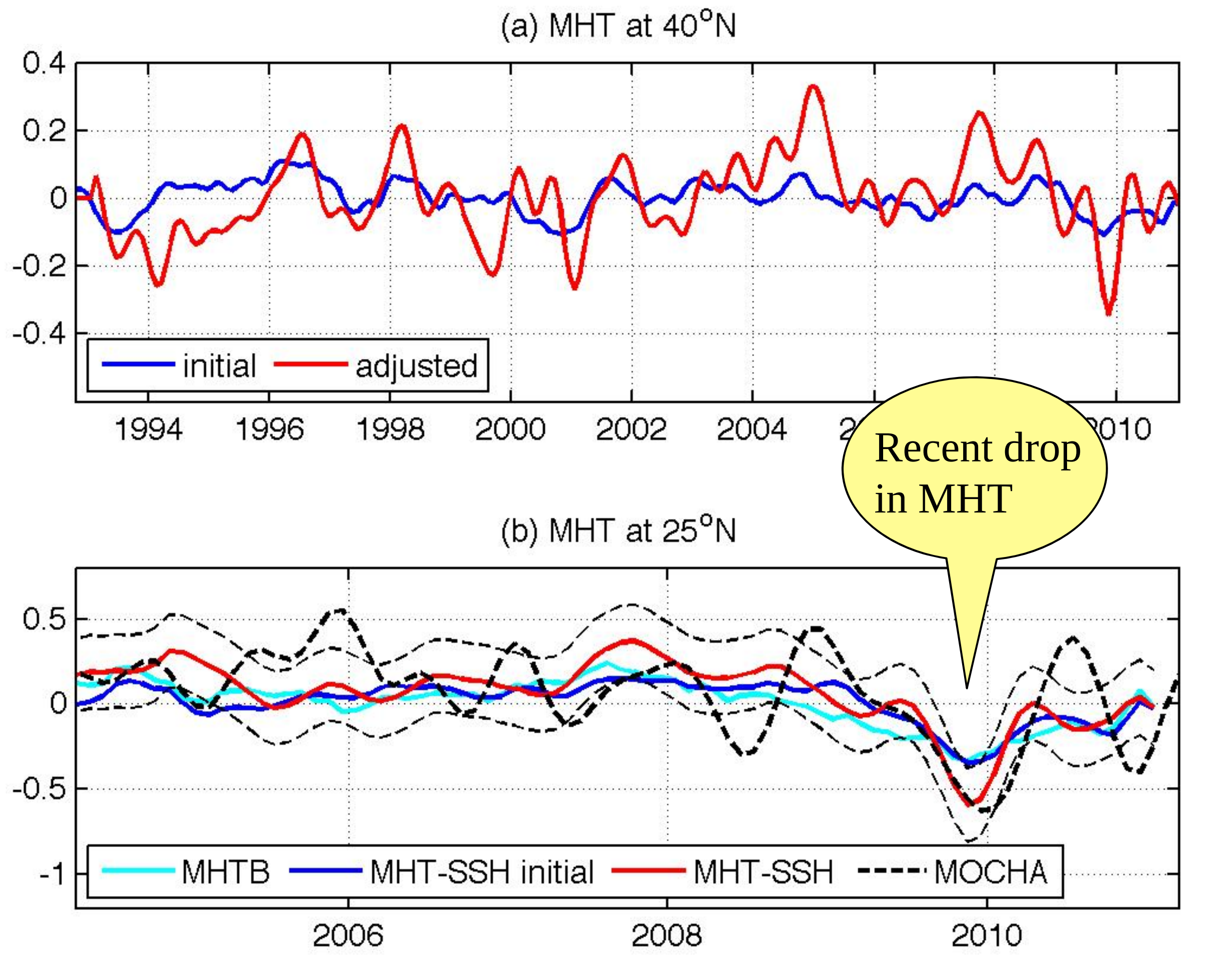
- Coherent MHT anomalies over 1-6 years
- Minima in 1999-2001 and 2009-2010
- Maximum 2002-05



Comparison with MHT Observations

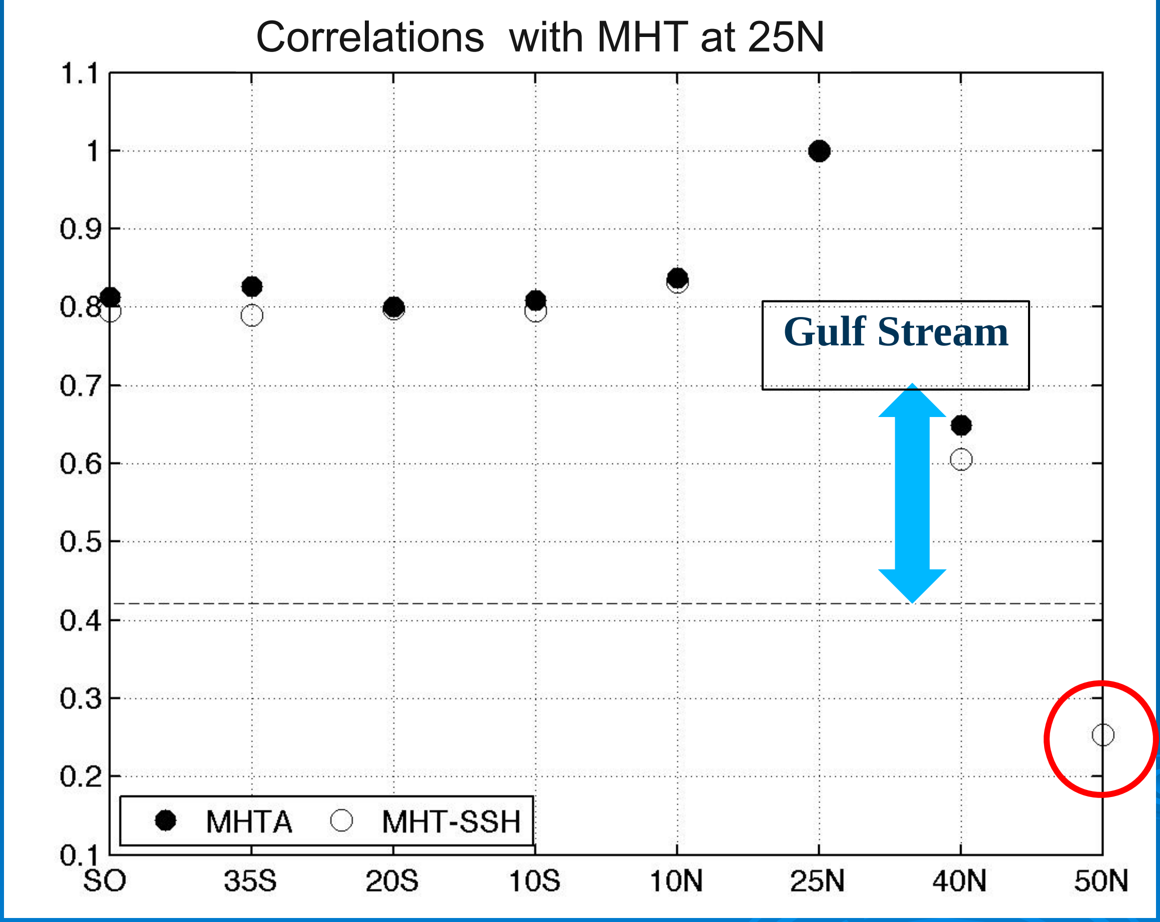
40ºN: MHT adjusted to obs (Willis 2004)

25ºN vs. MOCHA: *within error bars after 40ºN adjustment*

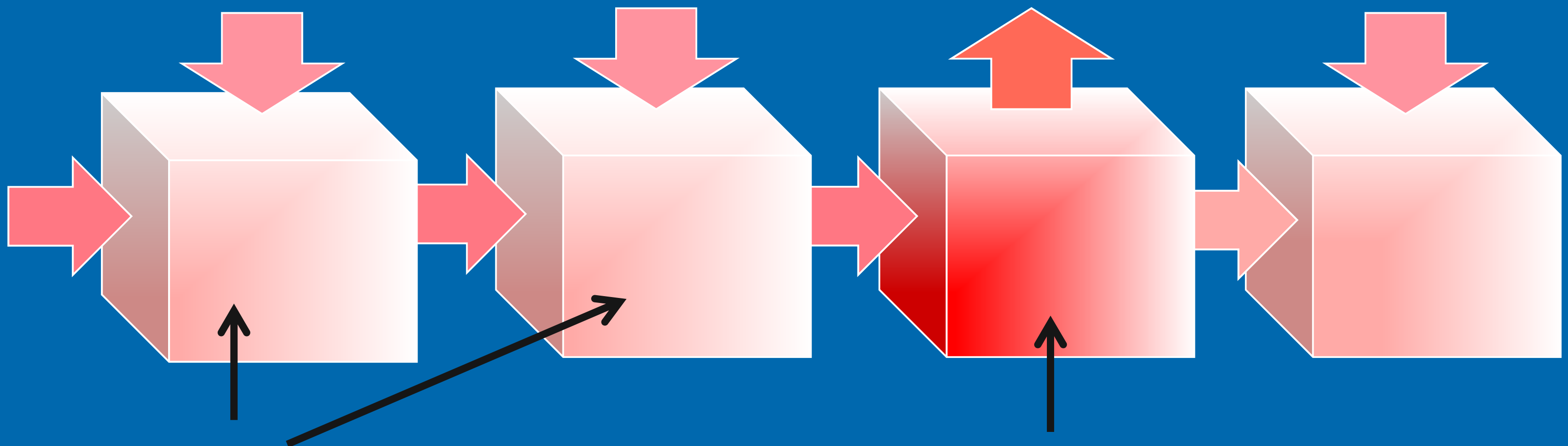


Coherence of Meridional Heat Transport

- High correlations with 25°N (MOCHA at 26.5°N)
- Not significant north of 40°N (even lagged)



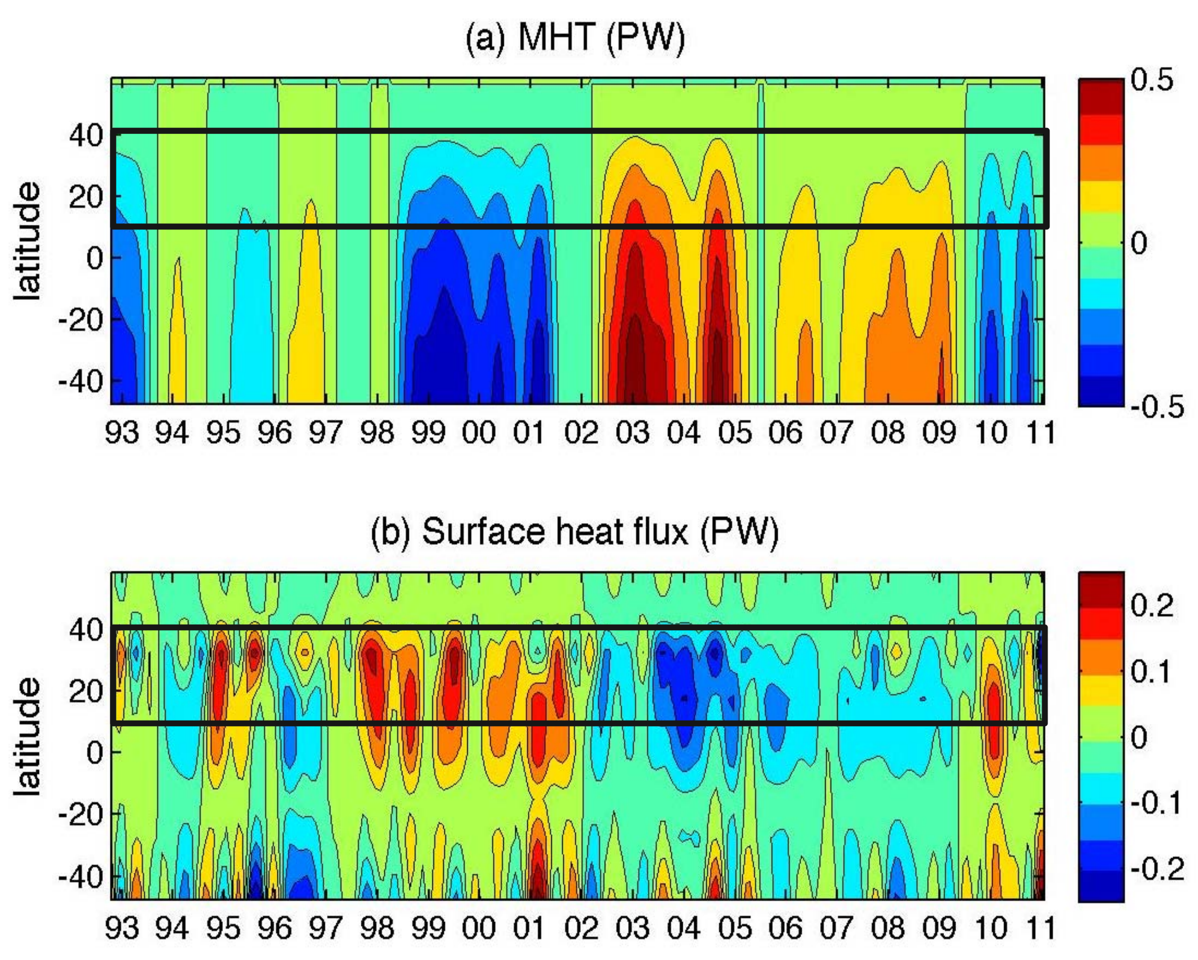
What Creates Coherence in MHT Estimates?



South Atlantic: Flux Q balances heat storage dH/dt ⇨ no HTC and no change in MHT

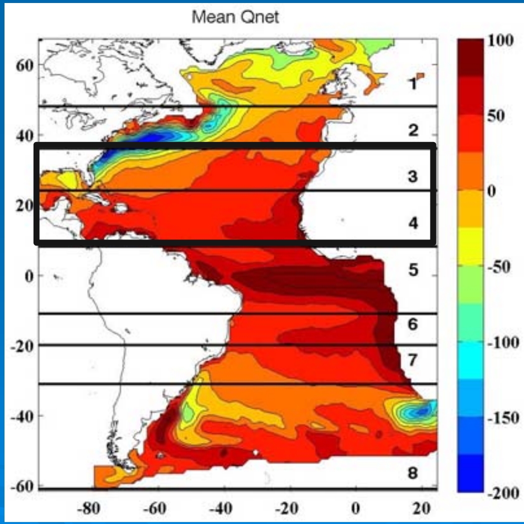
Large anomalies in tropics & North Atlantic set MHT in South Atlantic

MHT Feeds Surface Fluxes

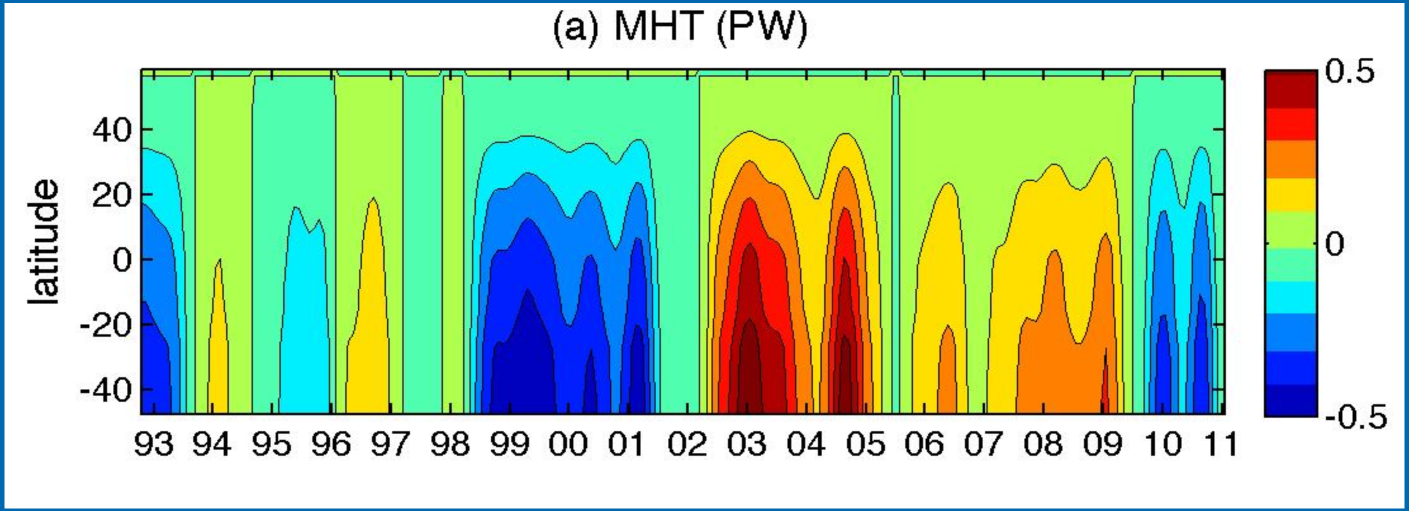


Increase in coherent MHT (from EOFs)

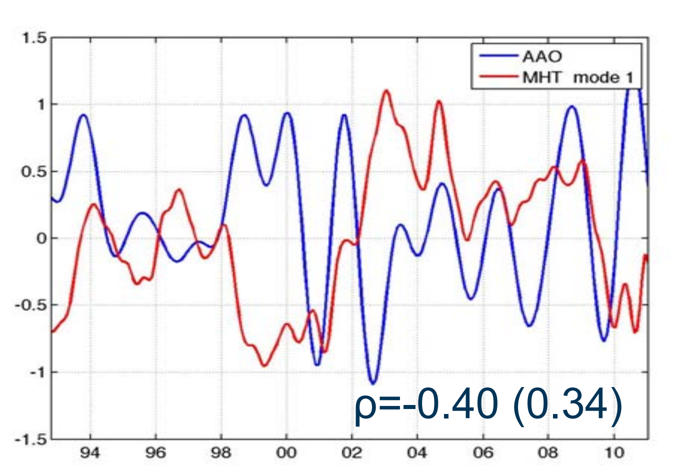
⇨ heat flux (loss) in subtropics



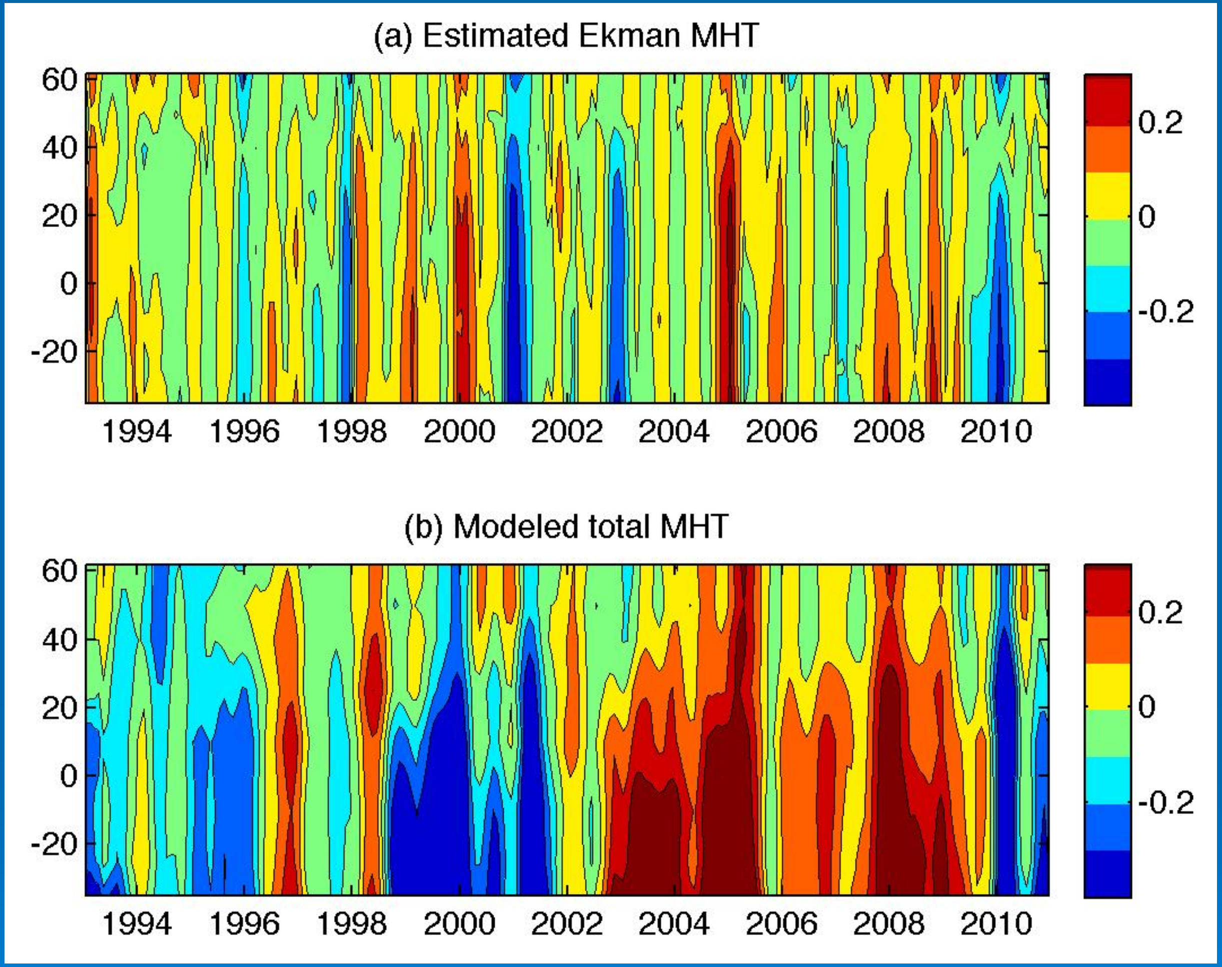
Origin of MHT Anomalies?



- MHT correlated with AAO
- (not NAO or tropical indices)
- AAO leads MHT by 2 years
- Strong westerlies followed by weaker MHT



Ekman contribution to MHT



Ekman contributes most to high frequencies

⇨ low frequency anomalies are geostrophic

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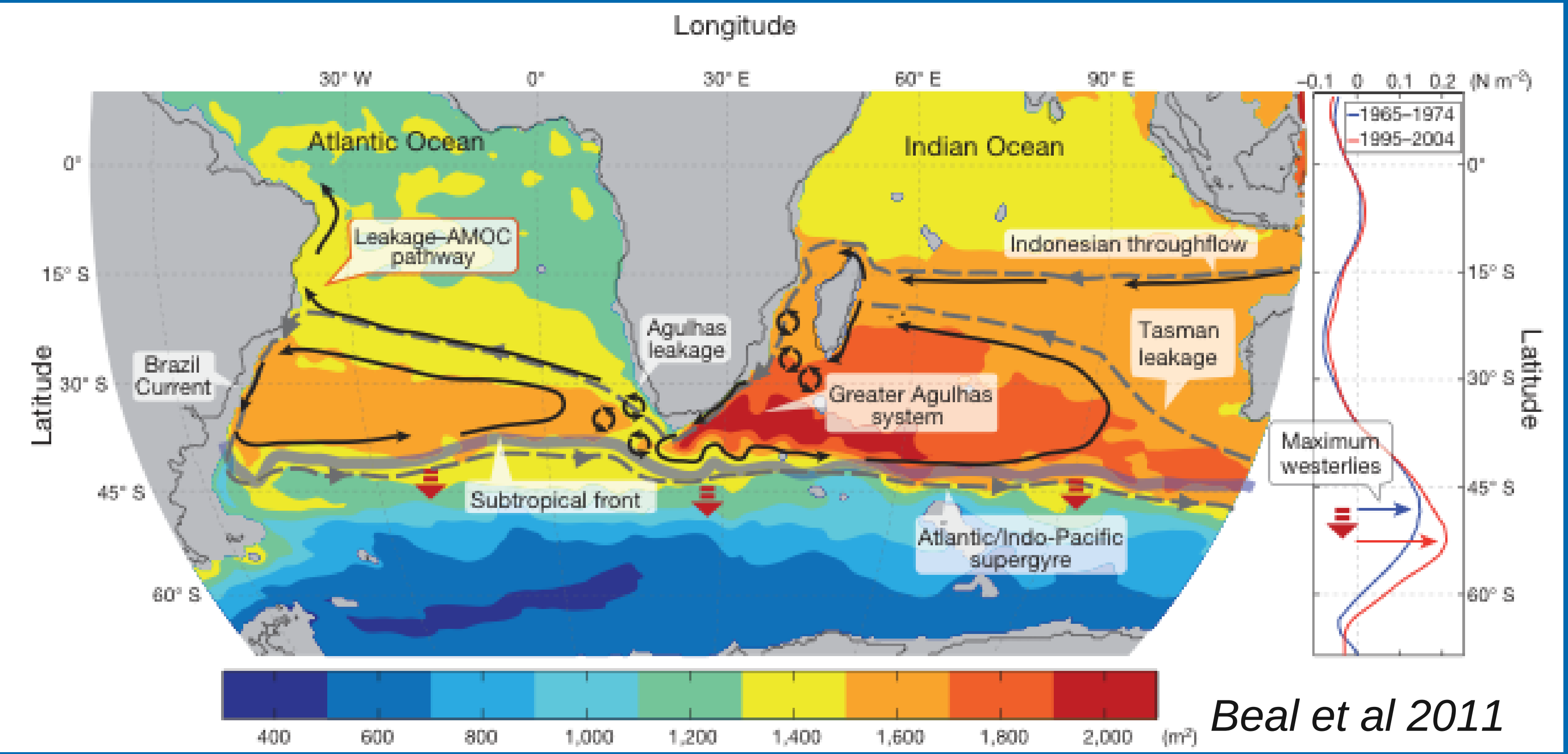
Southern Forcing

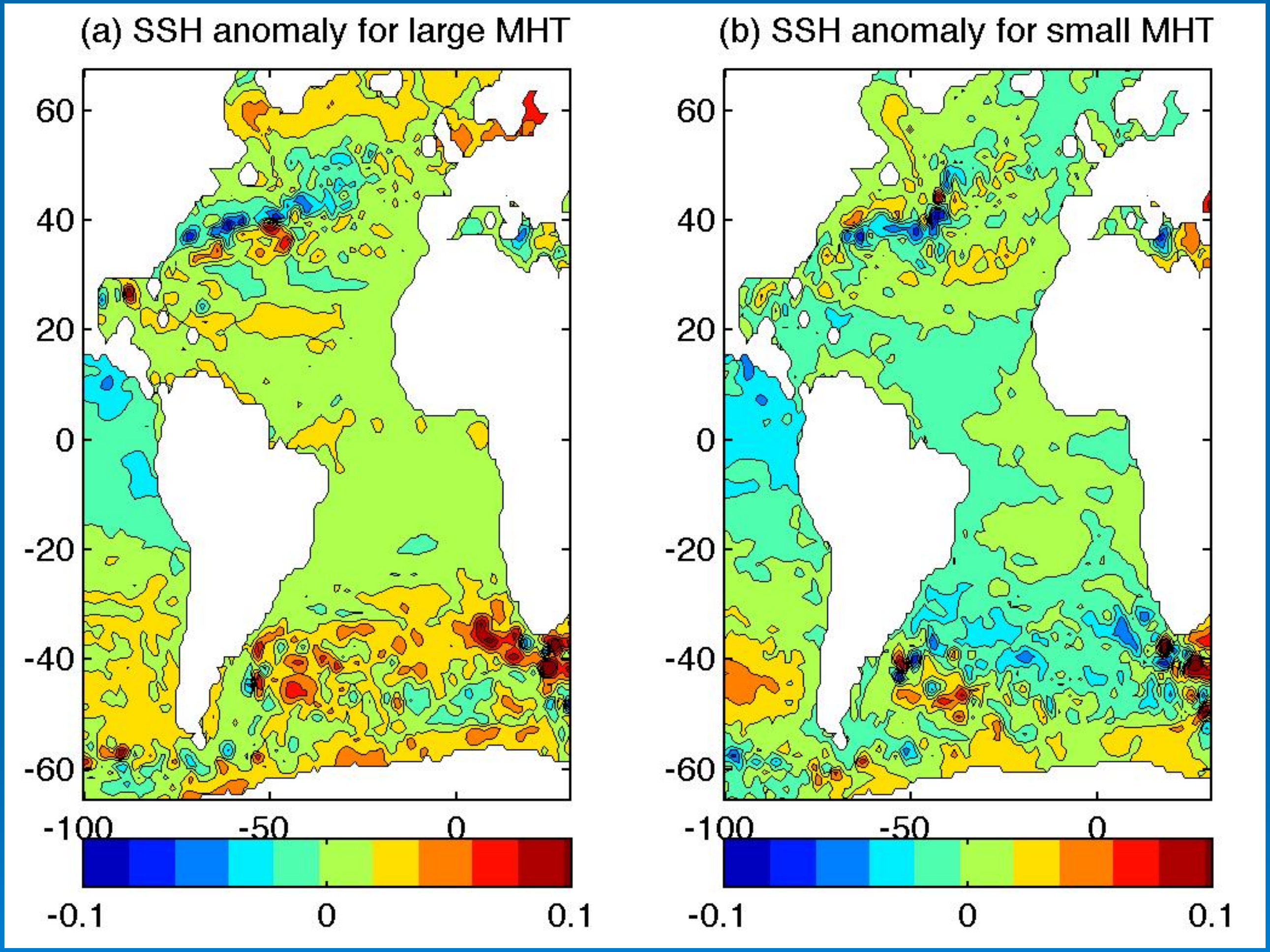


Beal et al 2011

Agulhas eddies inject heat and salt that influence AMOC

Southern Ocean winds control Agulhas Leakage & upwelling

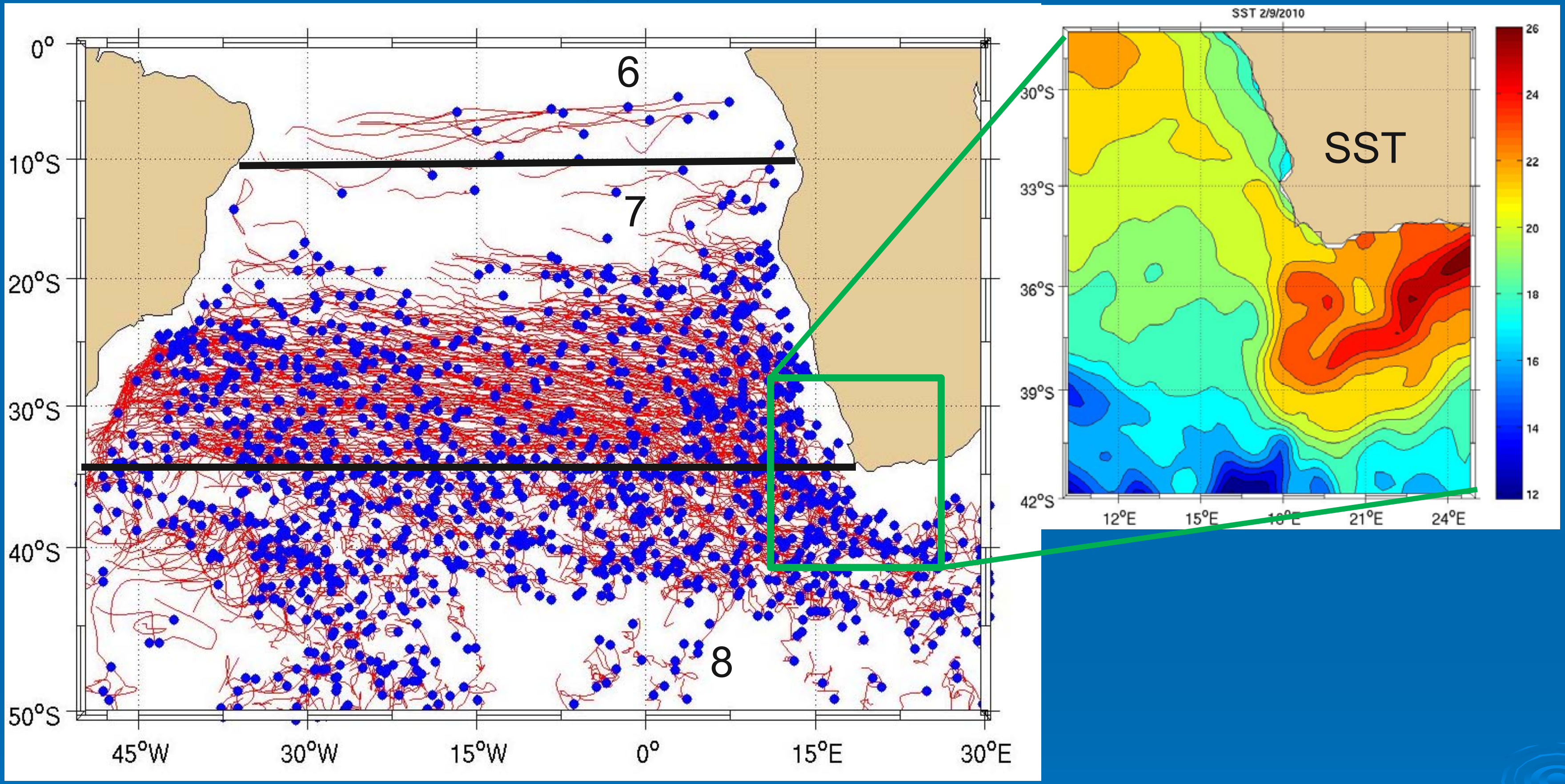
SSH Anomalies for High/Low MHT



High MHT corresponds to positive anomalies in South Atlantic

⇨ increased Agulhas Leakage?

Agulhas Eddies

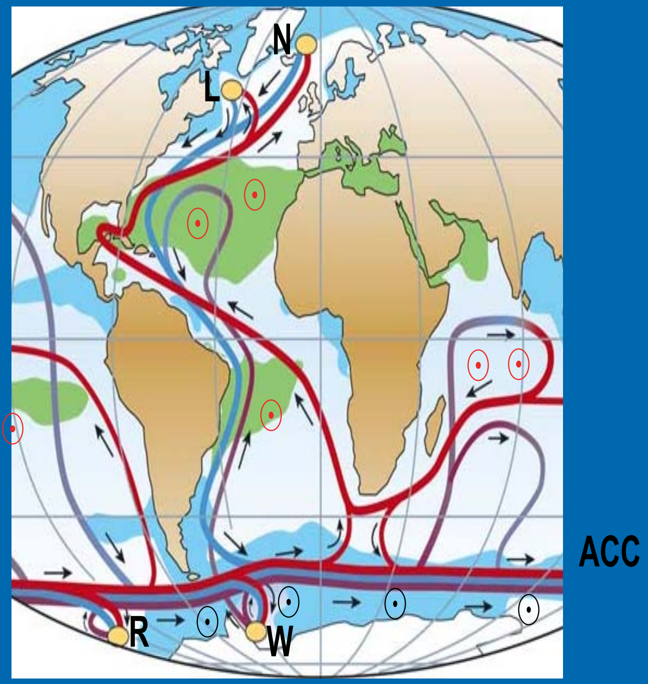


Warm Agulhas eddies flow westward and northward into Atlantic eddies (from satellite altimeter)

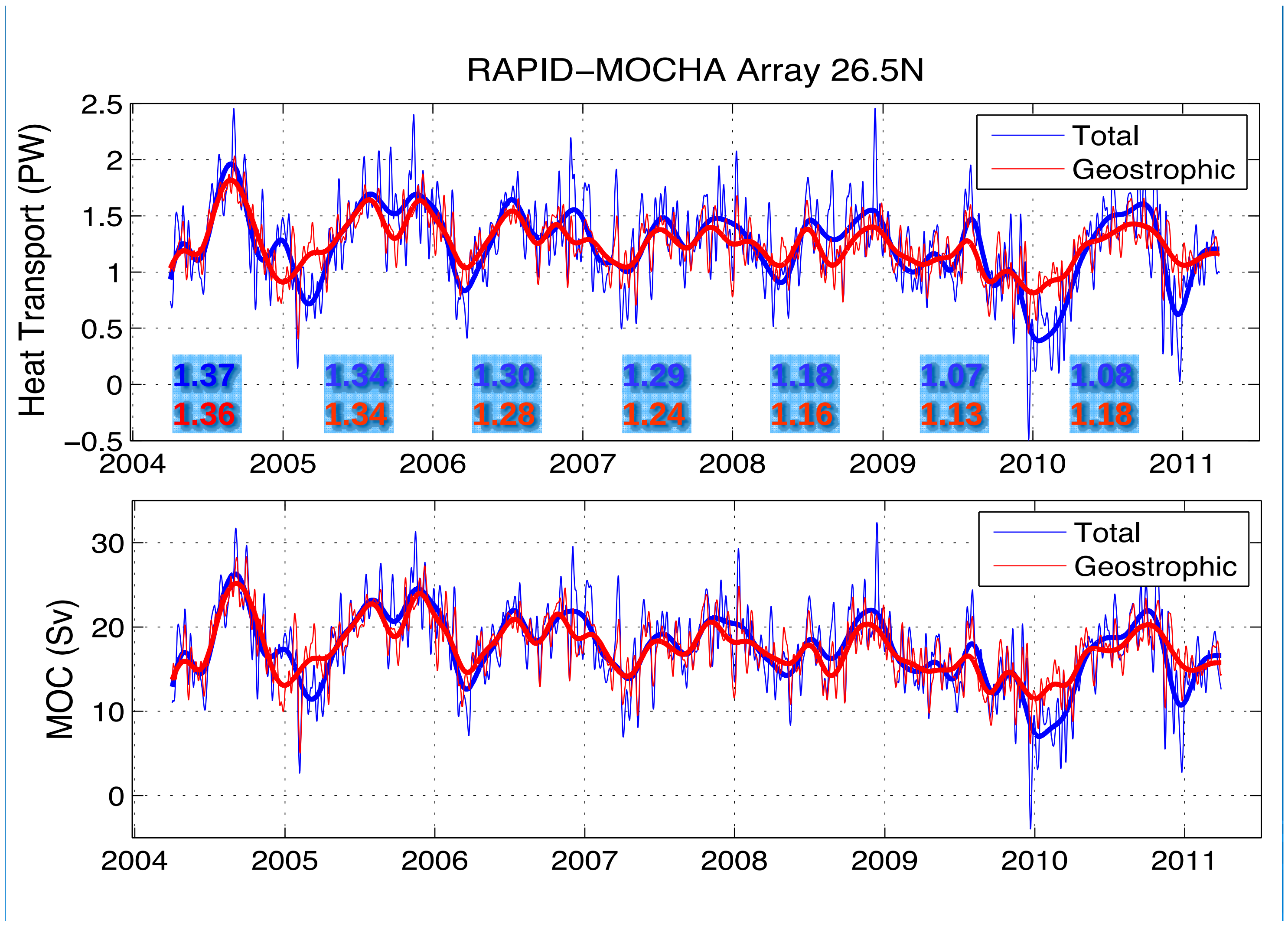
Chelton et al 2011

Summary

- MHT inferred from heat budget is coherent
- MHT anomalies “feed” subtropical air-sea interaction
- RAPID/MOCHA MHT shows strong Ekman contribution
- High frequency MHT anomalies from Ekman advection
- Low frequency anomalies: heat transport from Agulhas?



MHT and MOC Co-Vary



courtesy W. Johns

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Model Equations

- Predict thermosteric sea level η_H
- Surface heat forcing Q_{net}
- Assimilation of observations of TSL with Kalman filter
- Heat transport convergence (HTC) as residual ("unknown control')

$$\frac{\partial \eta_H}{\partial t} = \frac{\alpha Q_{net}}{\rho c_p} + HTC$$

$$\eta_H = TSL \quad \text{(assimilation)}$$

Model B Equations

- Add mass contribution to sea level η_M
- Surface freshwater fluxes: GPCP & OAFlux
- Assimilate SSH & equivalent water thickness EWT (GRACE, projected onto model EOFs, Chambers & Willis)
- Neglect salinity

Model B: Add mass budget (2002-2010)

$$\frac{\partial \eta_M}{\partial t} = P - E + MTC$$

$$\eta_M = EWT$$

(assimilation)

$$\eta_M + \eta_H = SSH$$

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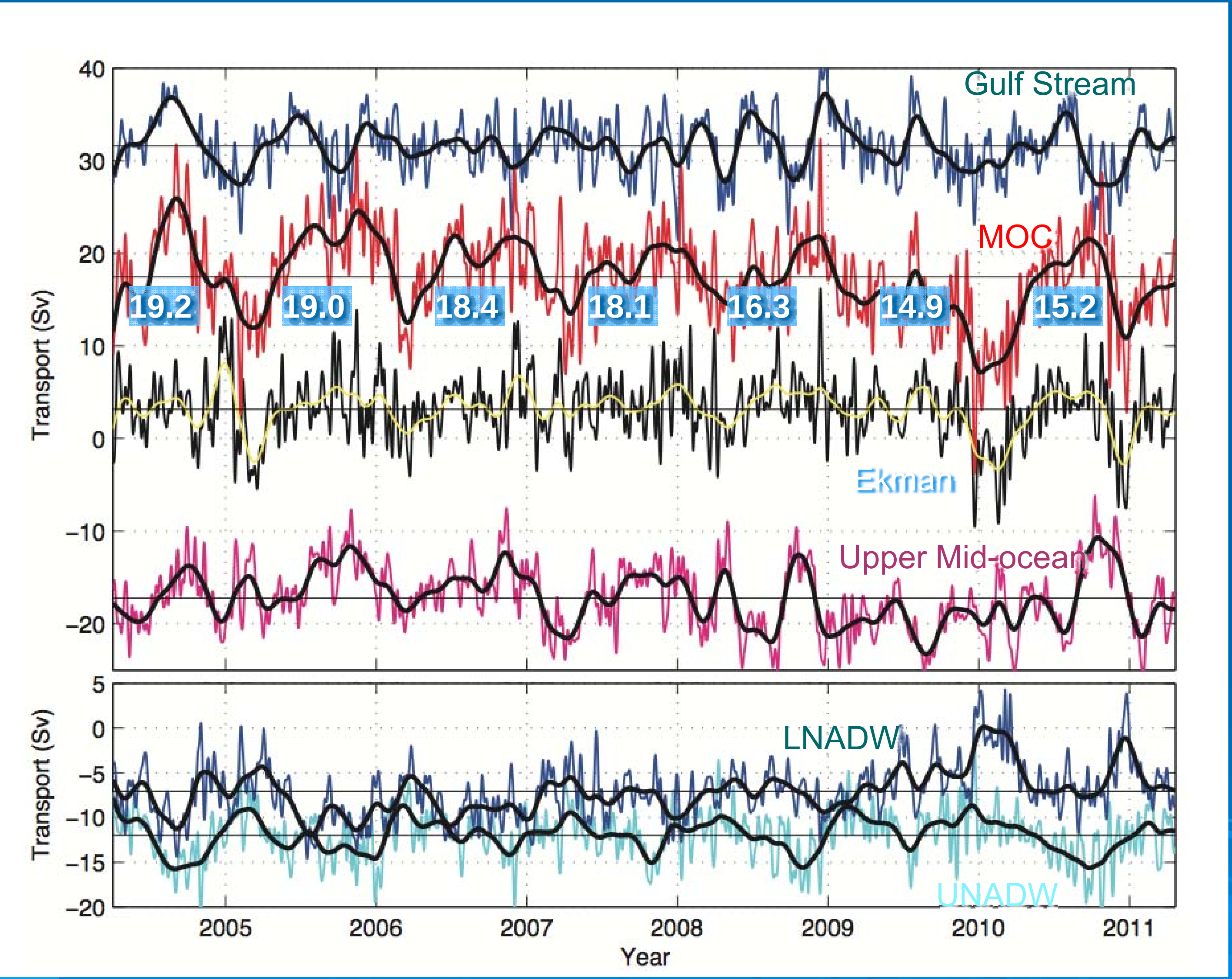
MOC and Transport Components

Upper Limb

Lower Limb



2004-2011 mean MOC strength: 17.5 Sv

McCarthy et al. (2012), submitted to GRL

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Comparisons with Assimilating Models

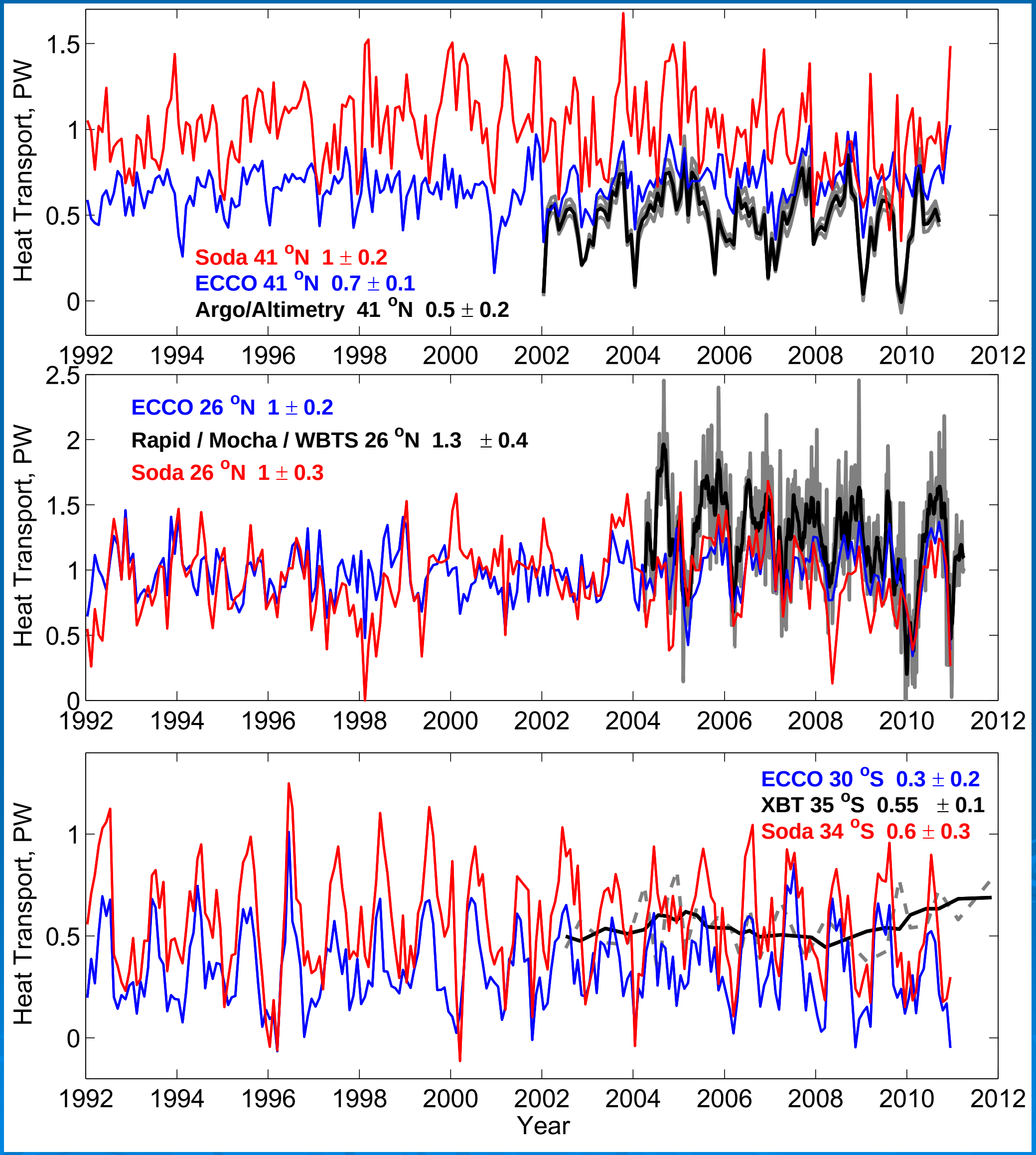
Direct measurements
ECCO and SODA

41°N: Argo/altimeter estimate
(Willis 2010)

26.5°N MOCHA: mean & anomalies underestimated

35°S XBT: sparsely sampled

Courtesy M. Baringer

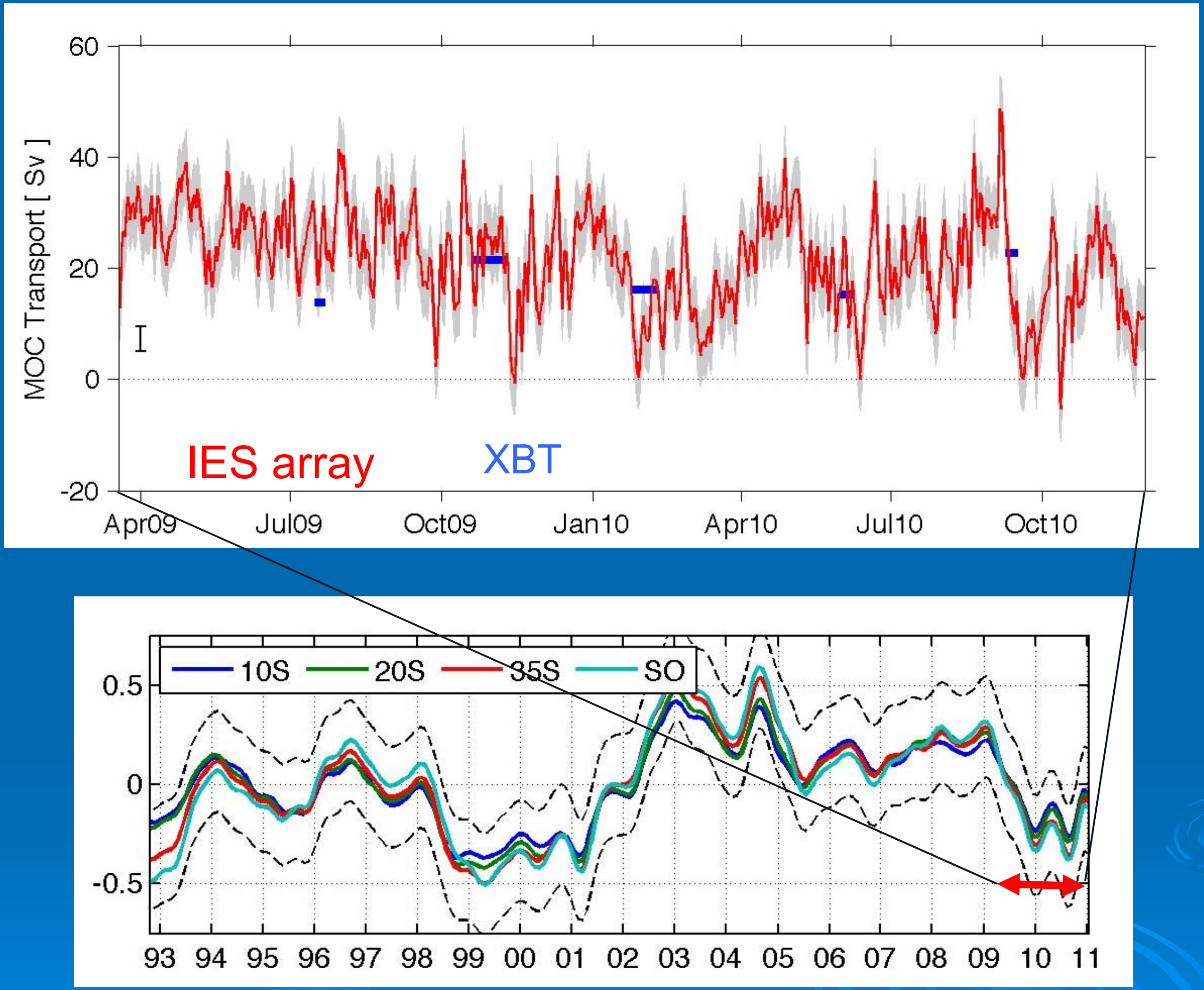


Comparison at 35ºS

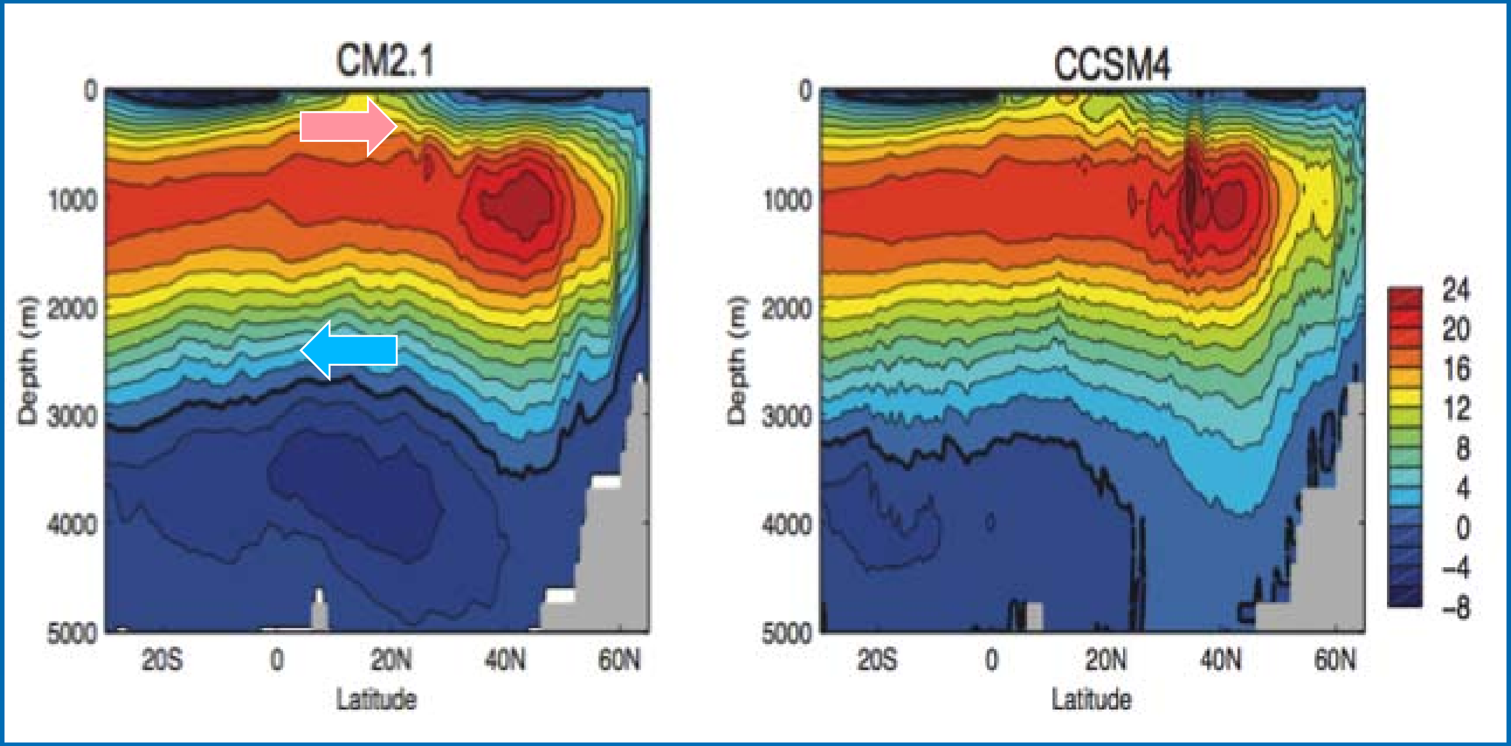
AMOC estimates

Meinen et al submitted

At 0.05 PW/Sv array anomalies are about 0.4PW



Atlantic Meridional Overturning Circulation (AMOC)



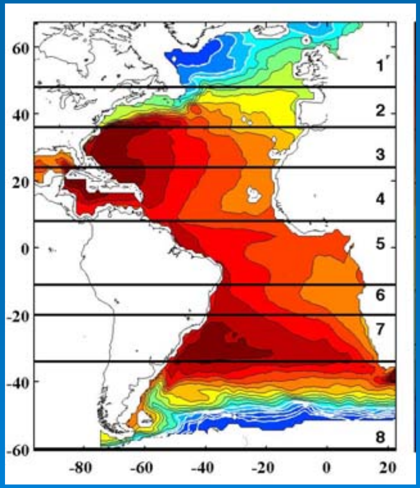
Thermohaline circulation. Warm water flows northward, cooler return flow below. Units are Sv (10^6 m^3/s)

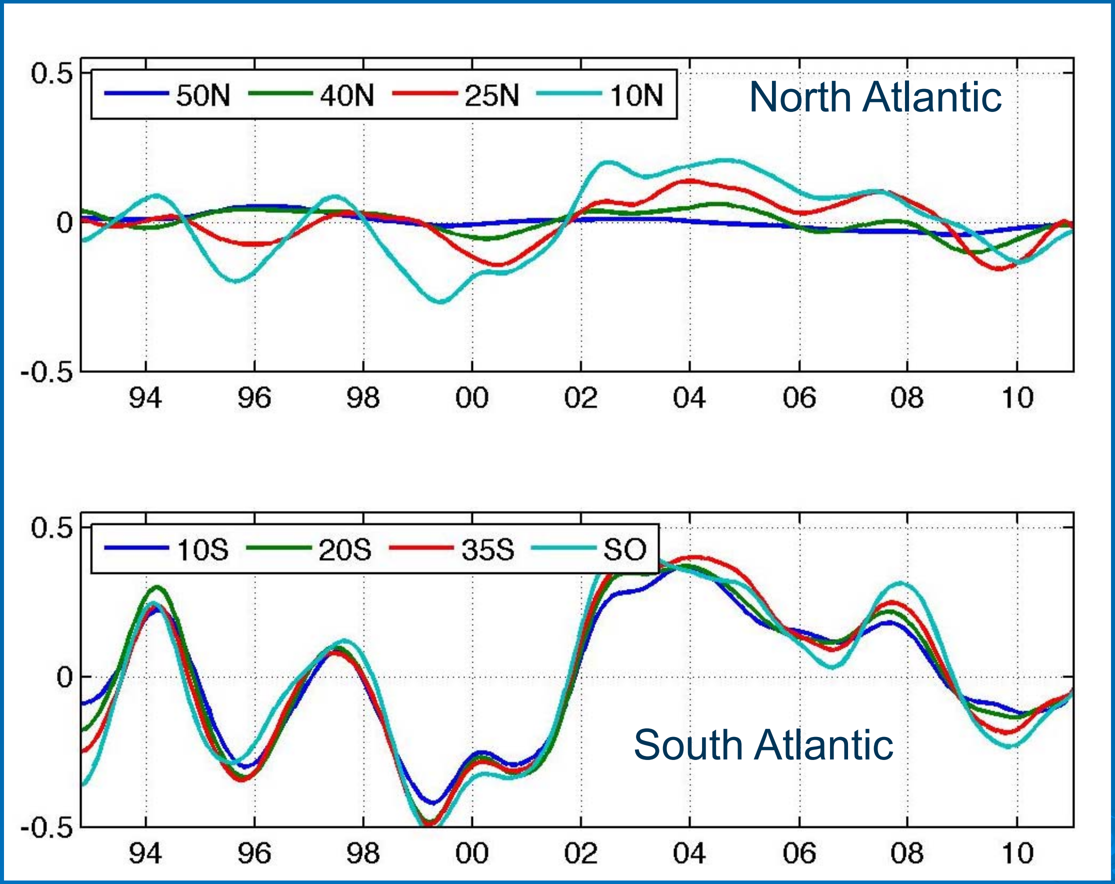
Msadek et al 2012

Meridional Heat Transport from HTC

Thermosteric sea level from in situ obs

Coherent anomalies in South Atlantic





Kelly, Thompson and Lyman, revised for J. Climate