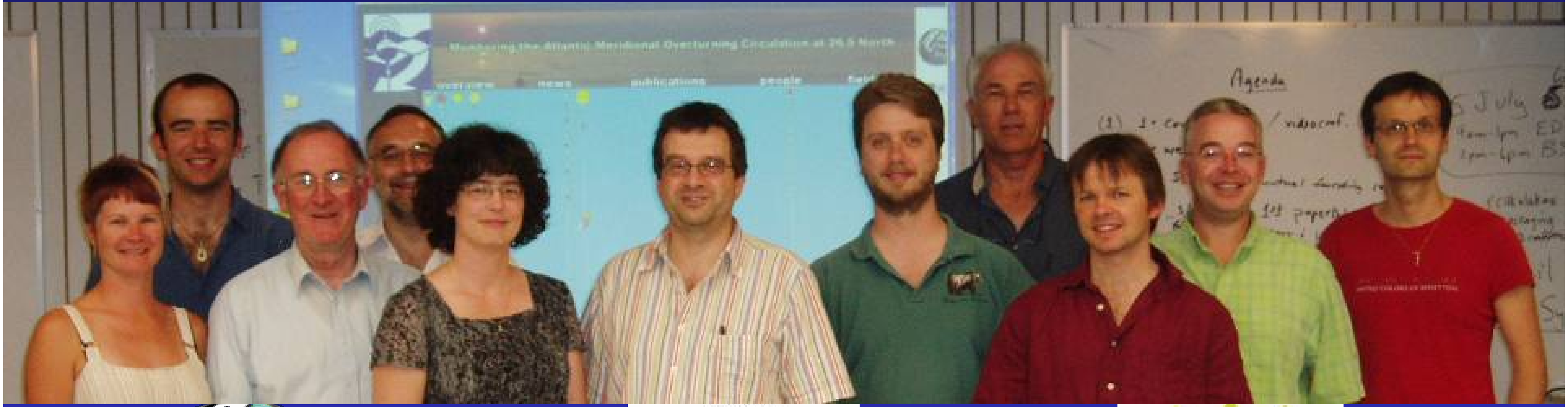
Monitoring the Meridional Overturning Circulation
presented by Molly Baringer



NERC – Rapid Climate Change

Jochem Marotzke
Harry Bryden
Stuart Cunningham
Torsten Kanzow
Joel Hirschi

NOAA Climate Program Office, WBTS

Molly Baringer
Chris Meinen

NSF Geosciences program, MOCHA

Bill Johns
Lisa Beal

Outline

Motivation

RAPID / MOCHA system

Does the system work?

MOC timeseries: April 2004 - Oct 2007

Vertical structure of the MOC

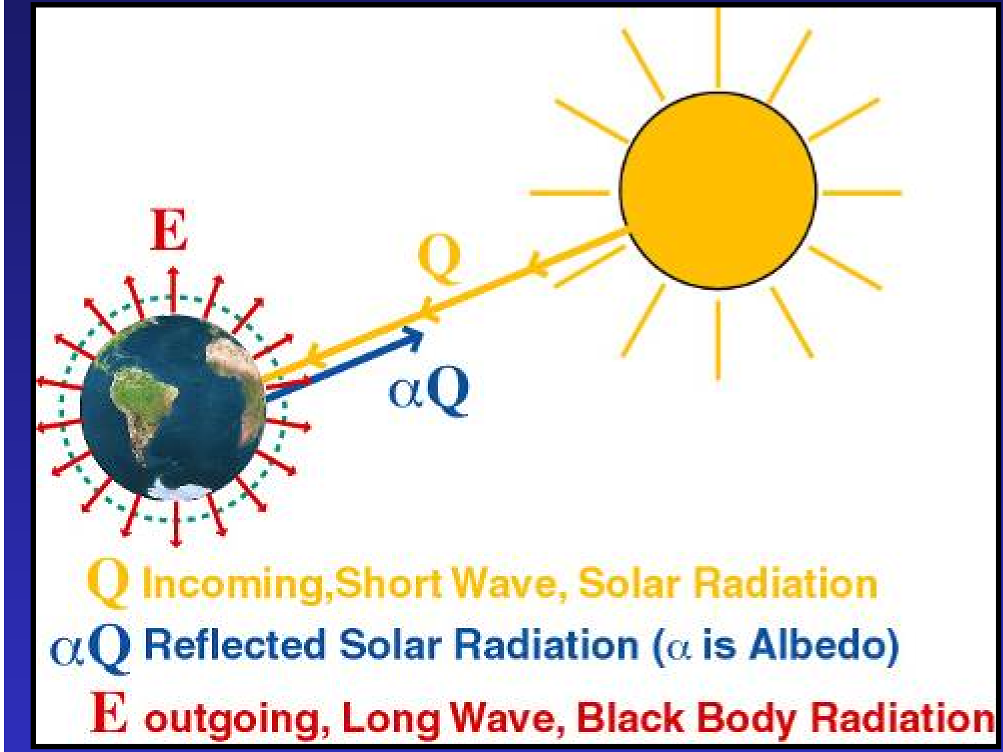
Variability of the MOC

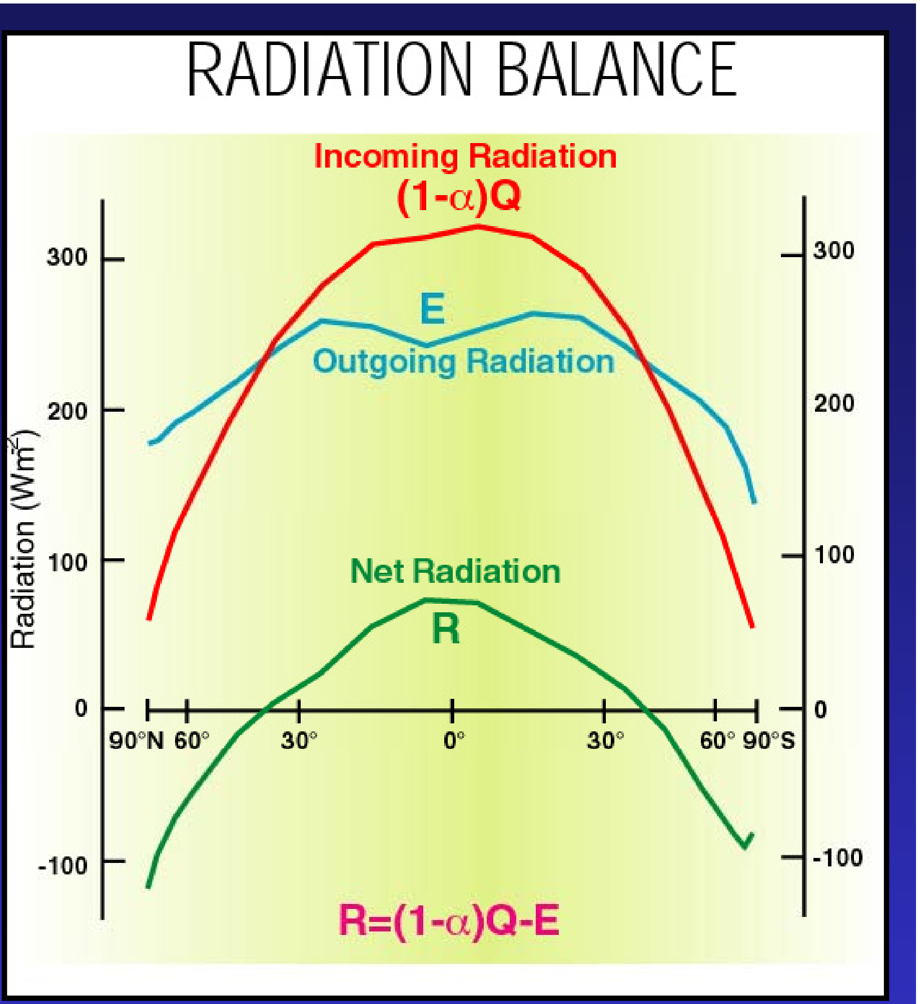
Heat transport

Conclusions

Next Steps

Global Energy Balance

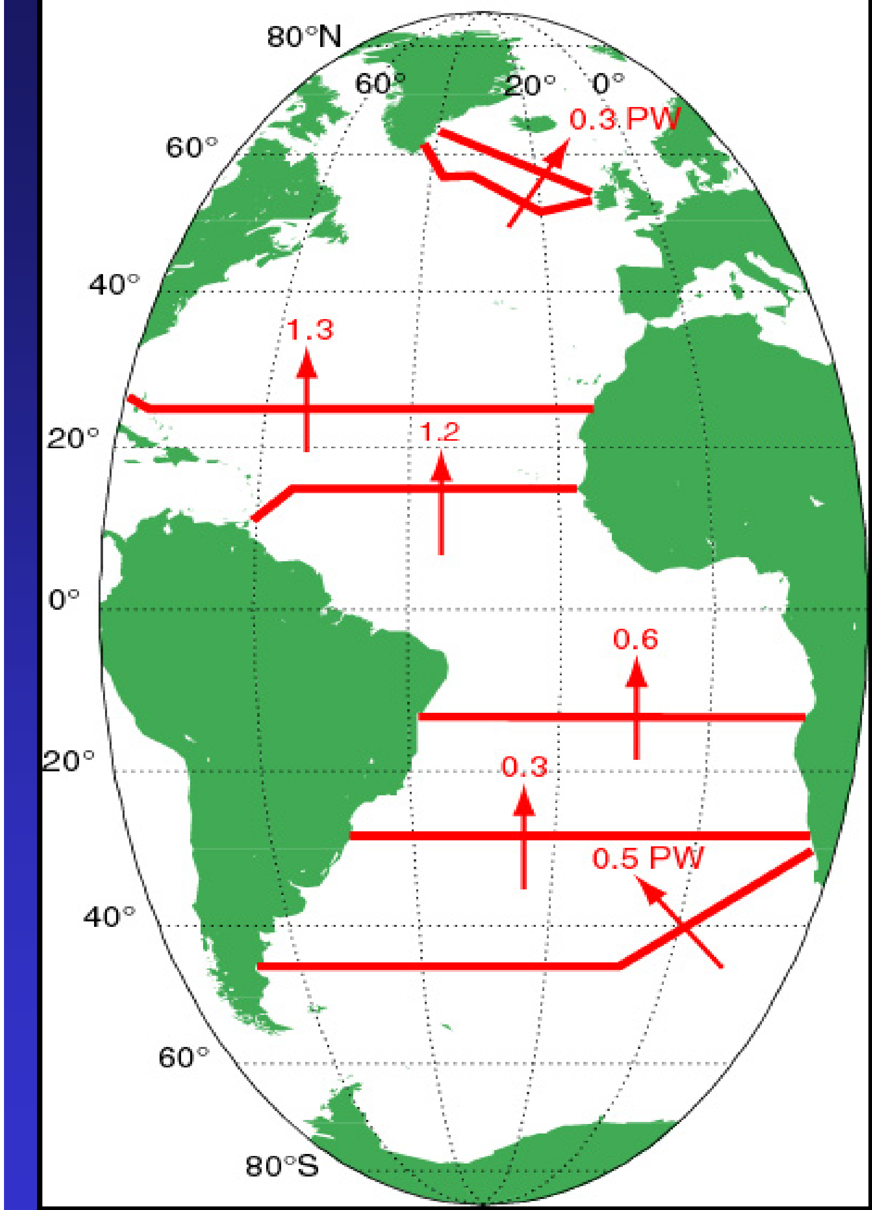




Bryden and Imawaki (2001)

Net heat loss at mid and high latitudes ==> Meridional heat transport

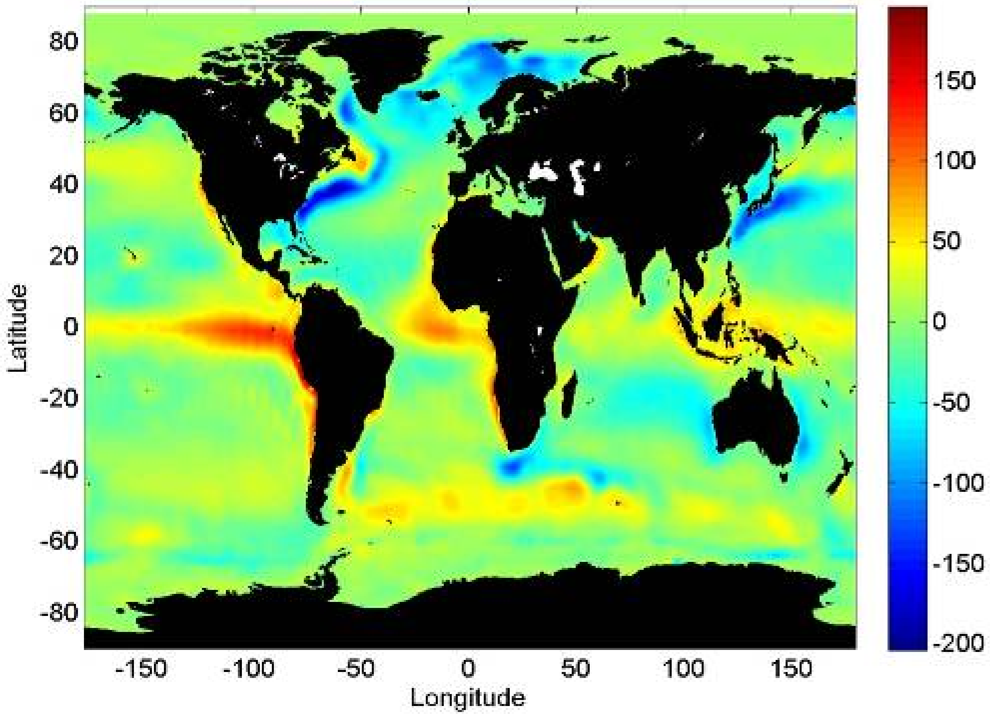
Atlantic Ocean Heat Transport
(Bryden and Imawaki, 2001)



Atlantic Ocean Heat Transport

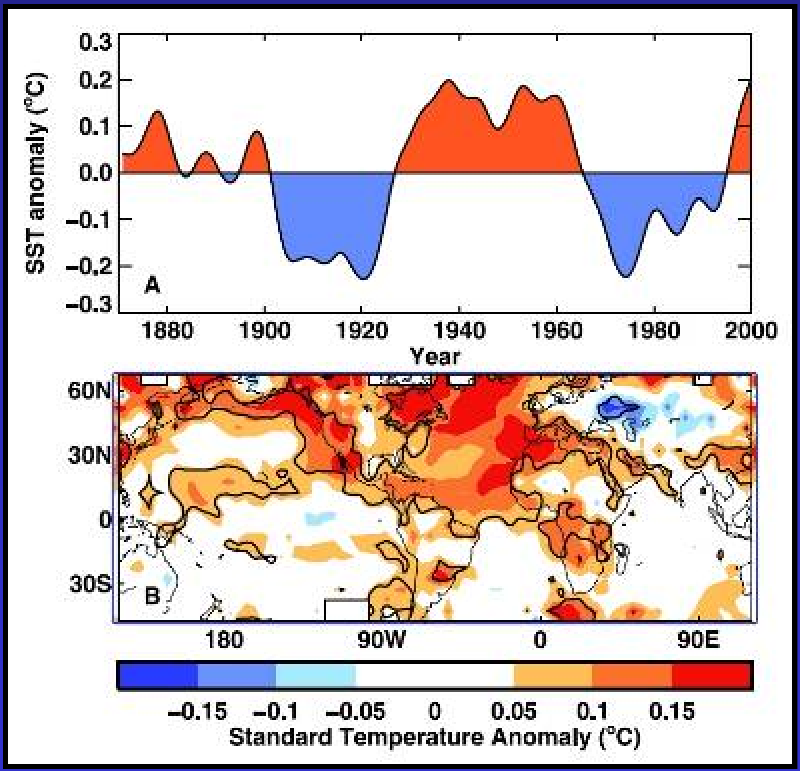
The Atlantic Ocean heat transport across 26.5°N accounts for 25% of the maximum poleward heat transport.

Annual Net Surface Heatflux (W/m2)



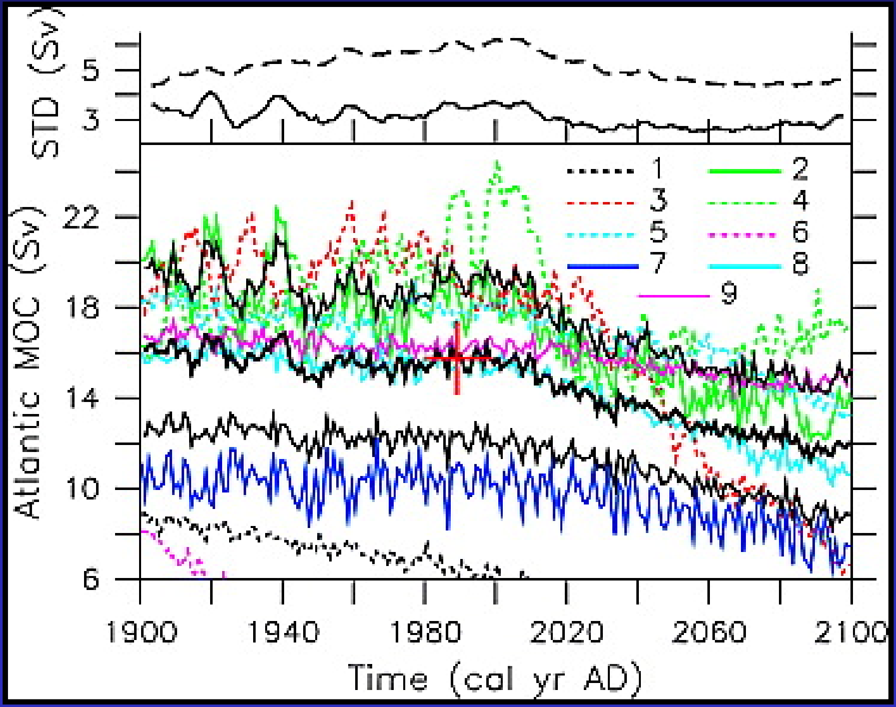
Climate variations / climate change:
What is the role of the Atlantic Meridional overturning circulation?

Will the MOC change in response to anthropogenic forcing? How much, how fast, and when?



Knight et al. (2005)

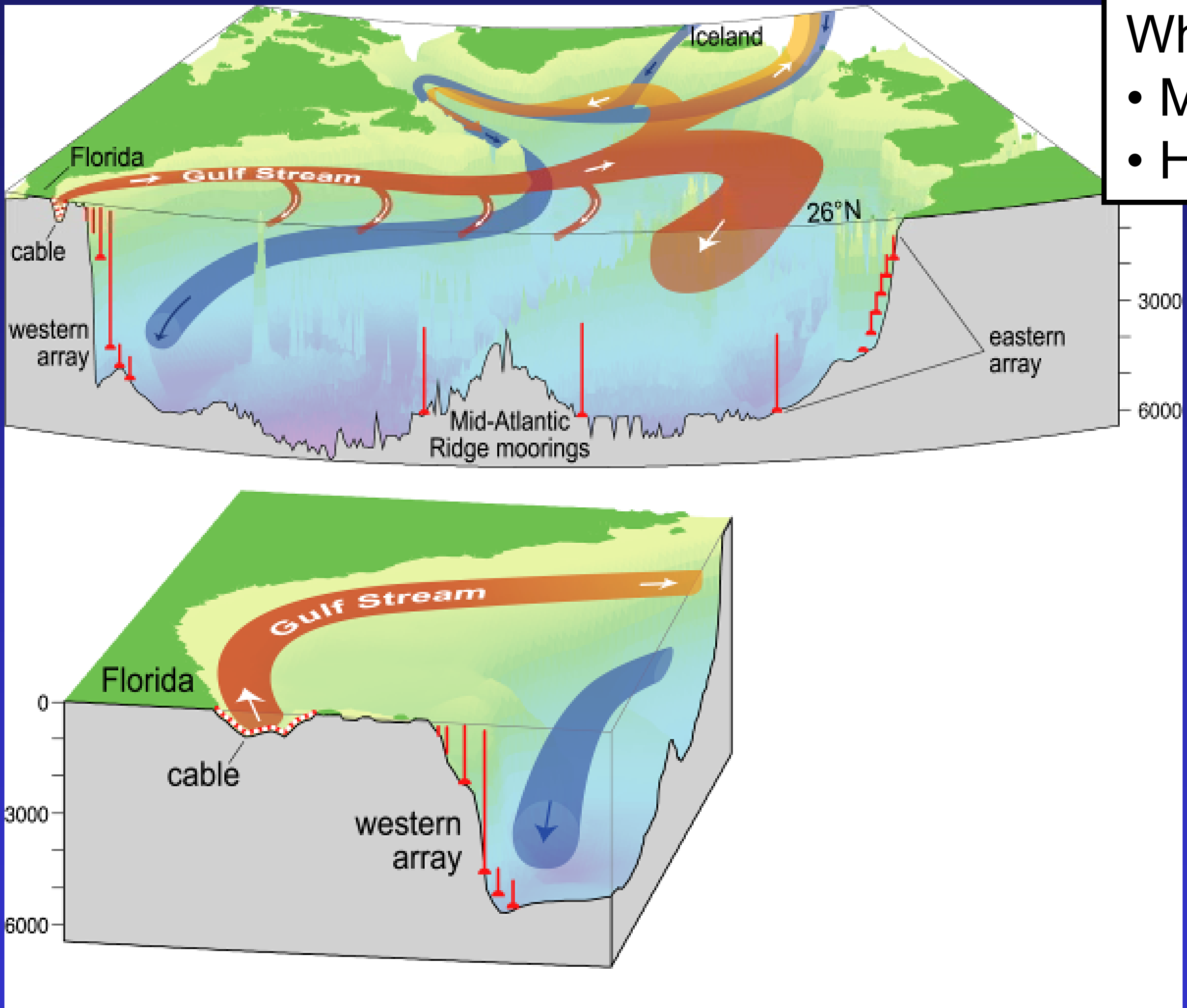
IPCC/AR4 A1-B scenario runs
(Schmittner, 2005)



What is the role of MOC change in interannual to multidecadal climate variability (AMO/AMV)?

RAPID-MOC/MOCHA

Monitoring the Atlantic Meridional Overturning at 26.5°N



Louise Bell/Neil White, CSIRO

Why 26.5°N?

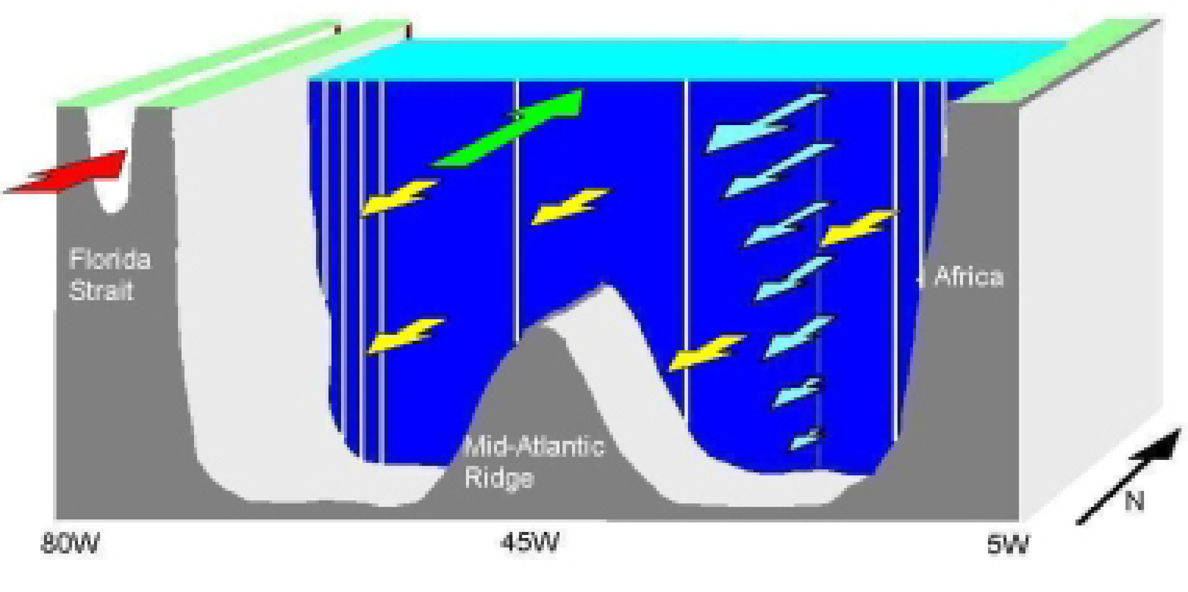
- Maximum heat transport
- History of measurements

Goal: *"To set in place a system for continuous observation of the meridional overturning circulation and northward heat transport in the Atlantic Ocean, with which to document its variability and its relationship to observed climate fluctuations, and to assess climate model predictions."*

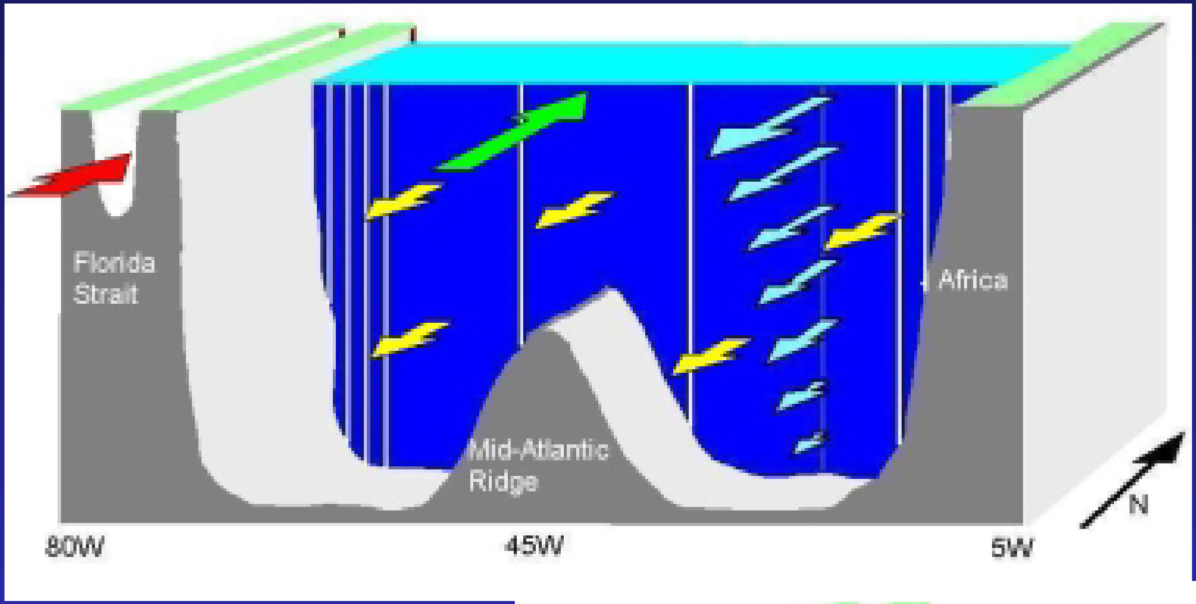
Specific Objectives:

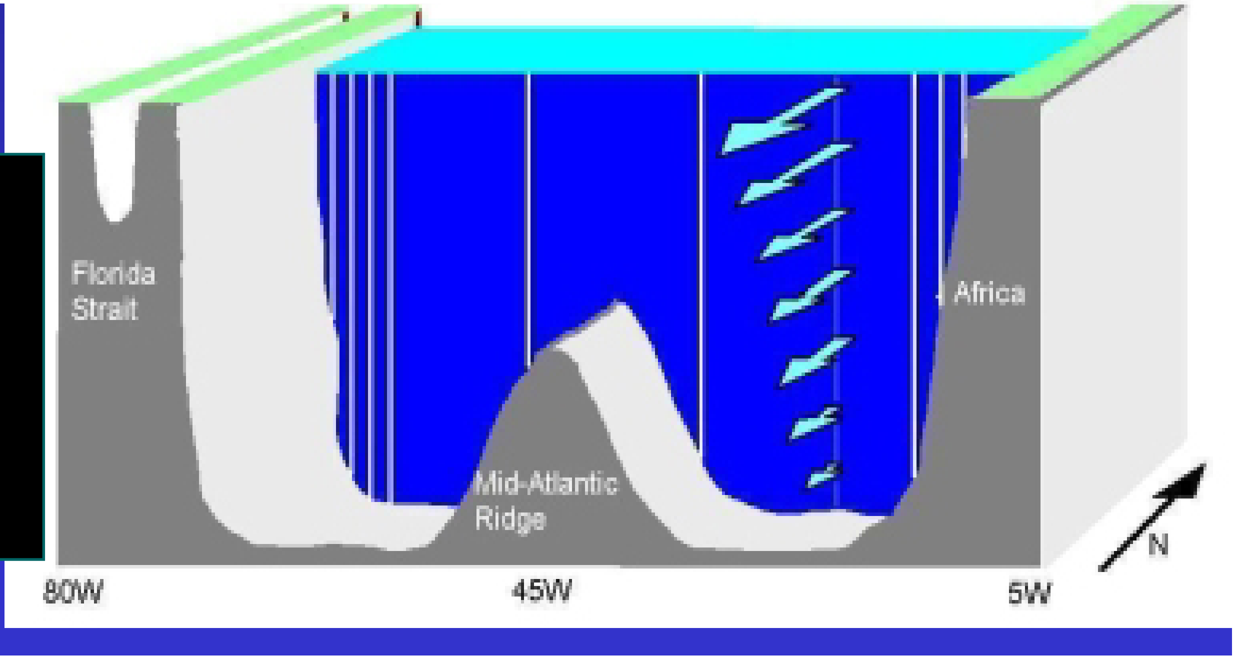
- *Determine the "present day" mean MOC & MHT at 26°N and year-to-year variability*
- *Determine the spectrum of MOC variability, and related mechanisms, to help optimize MOC observing systems*
- *Provide a benchmark of MOC strength and variability for climate and ocean synthesis models*

Flow Decomposition



Flow Decomposition

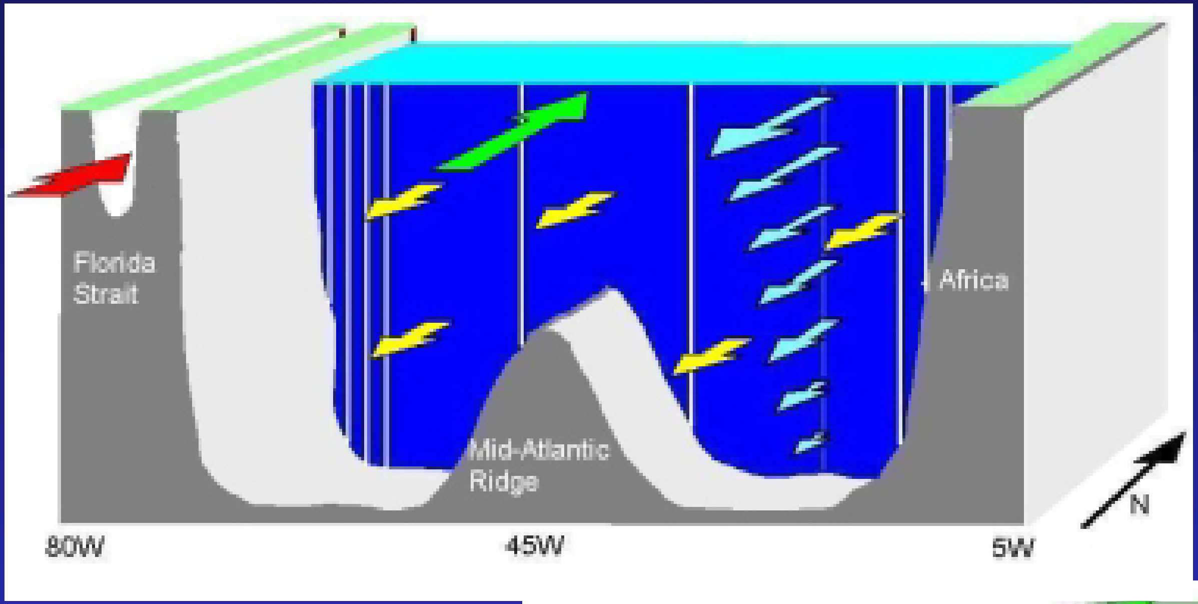


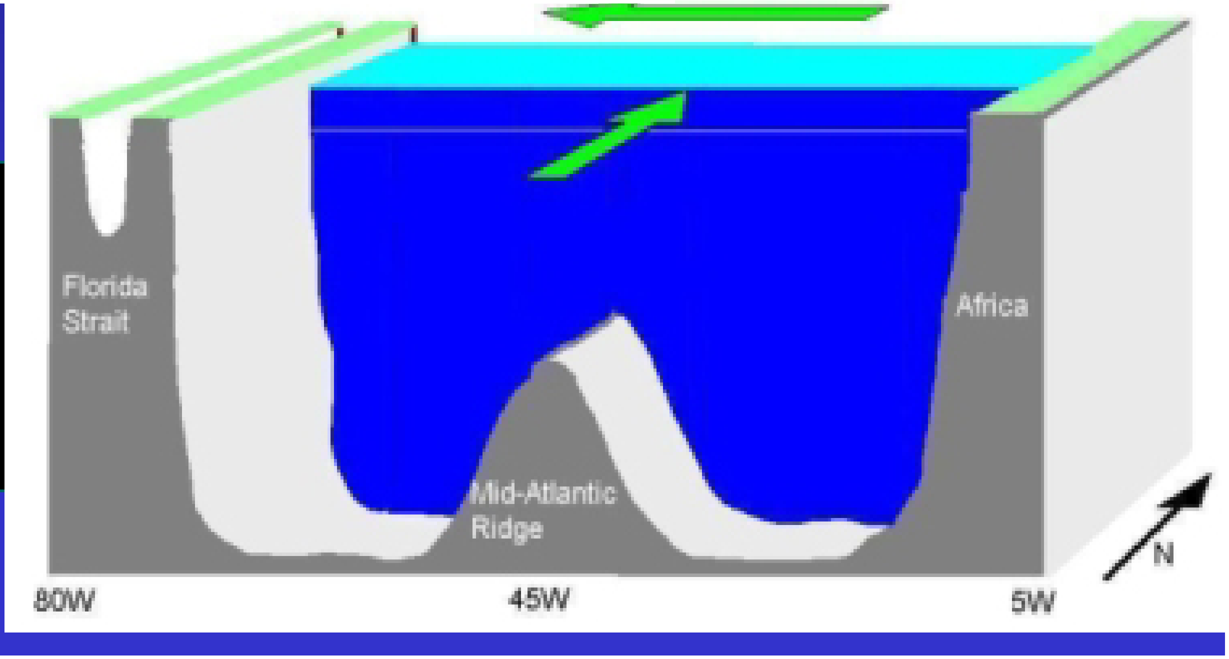


Light blue: Velocity determination from density measurements

Baringer March 2009

Flow Decomposition





Green: Velocity determination from wind measurements

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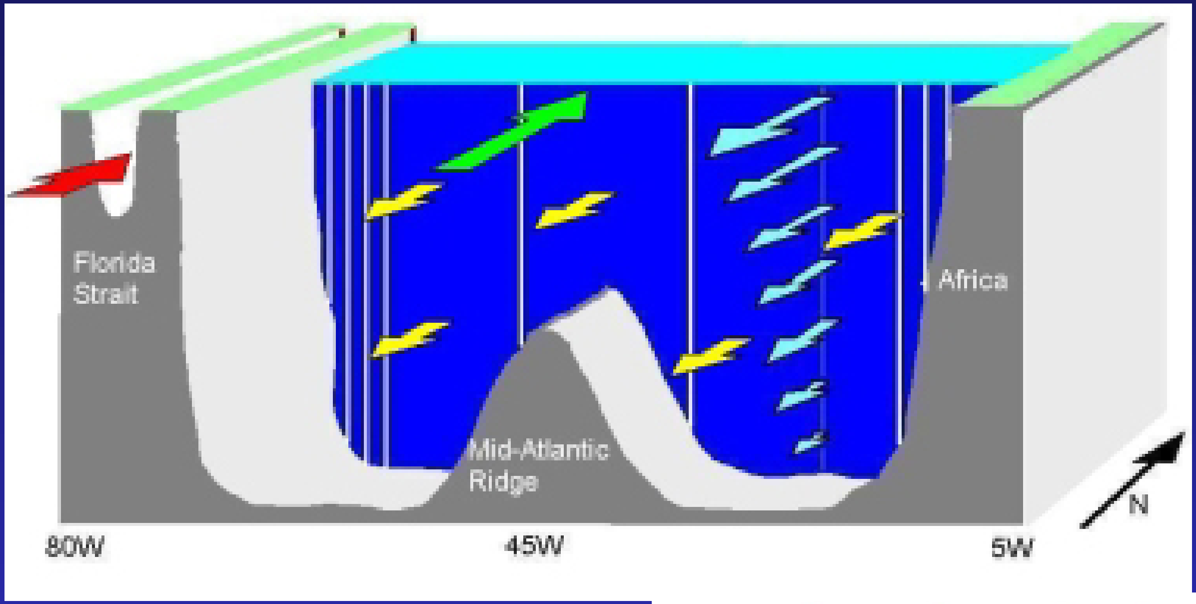
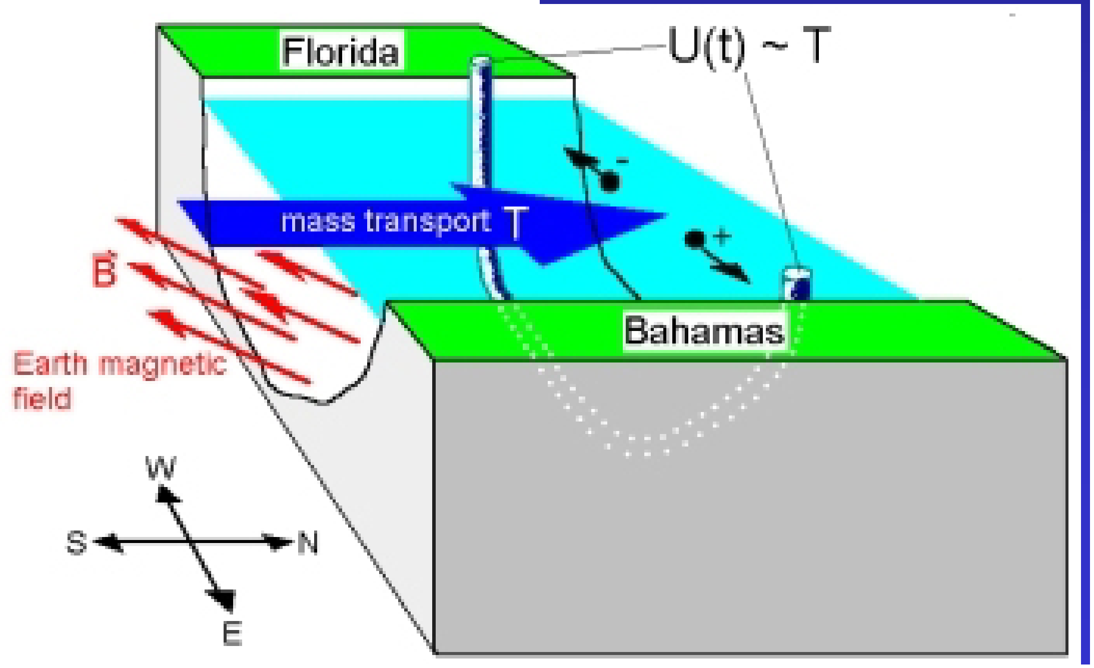
Flow Decomposition





Red: Florida Strait transport measurements with telephone cable

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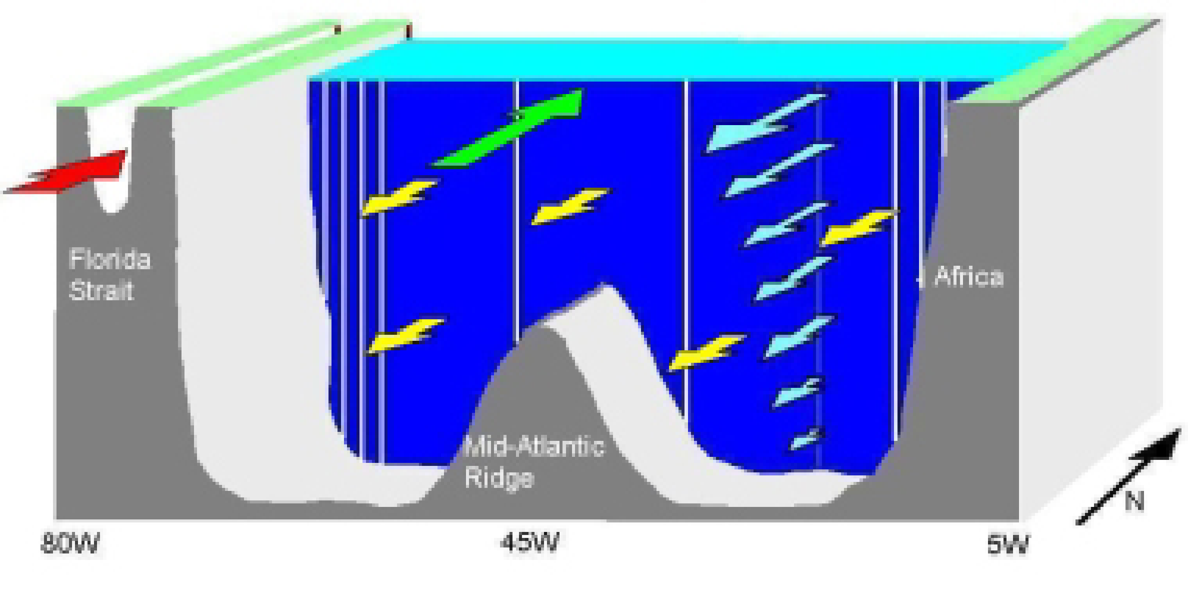
Flow Decomposition

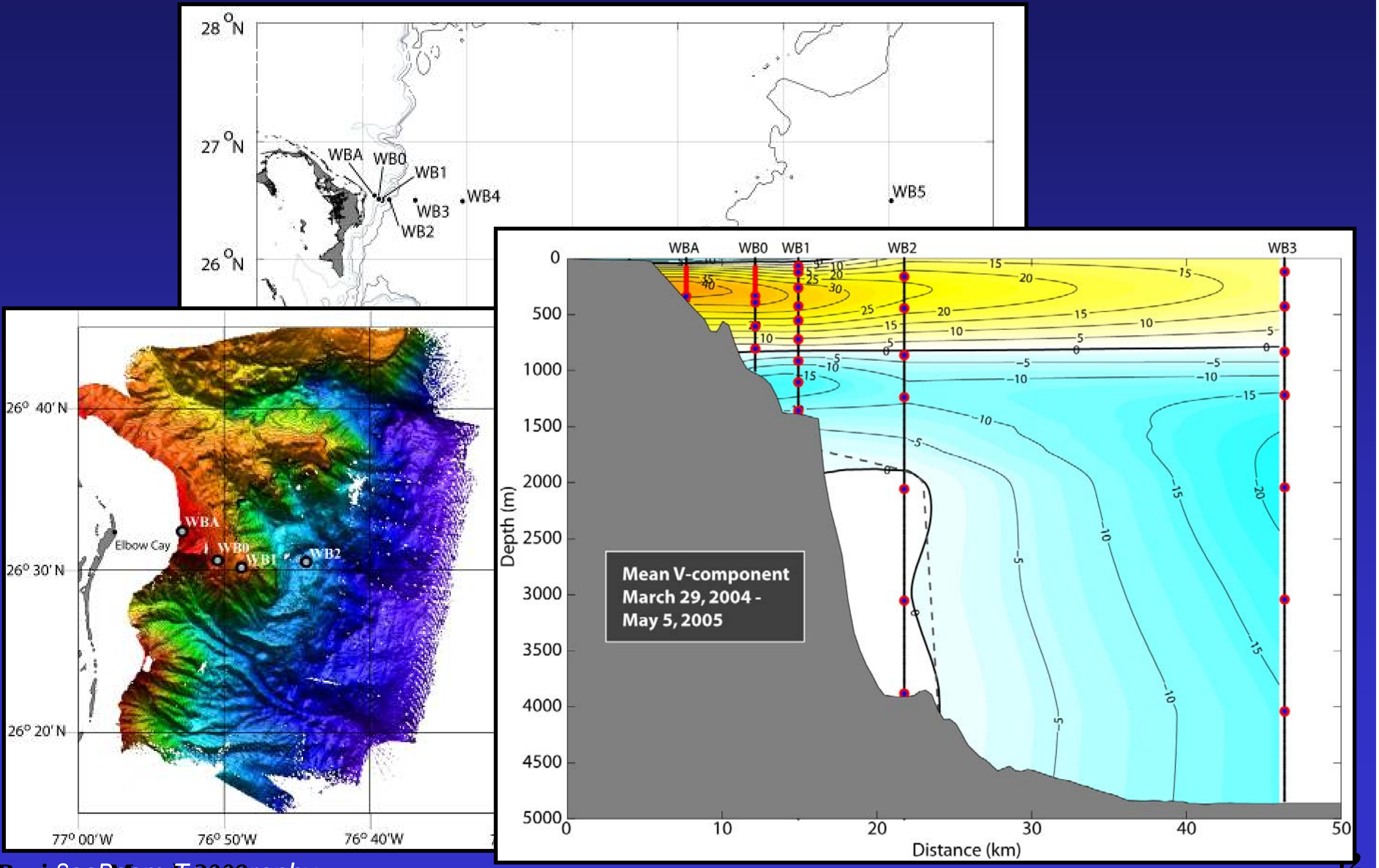


Yellow: Uniform correction for mass conservation

Validation:

- Tests in high-resolution models (Hirschi et al., 2005)
- Observed mass compensation by external (barotropic) flow (Kanzow et al., 2007)

Western Boundary Array



Mean V-component
March 29, 2004 -
May 5, 2005

SeaBeam Topography

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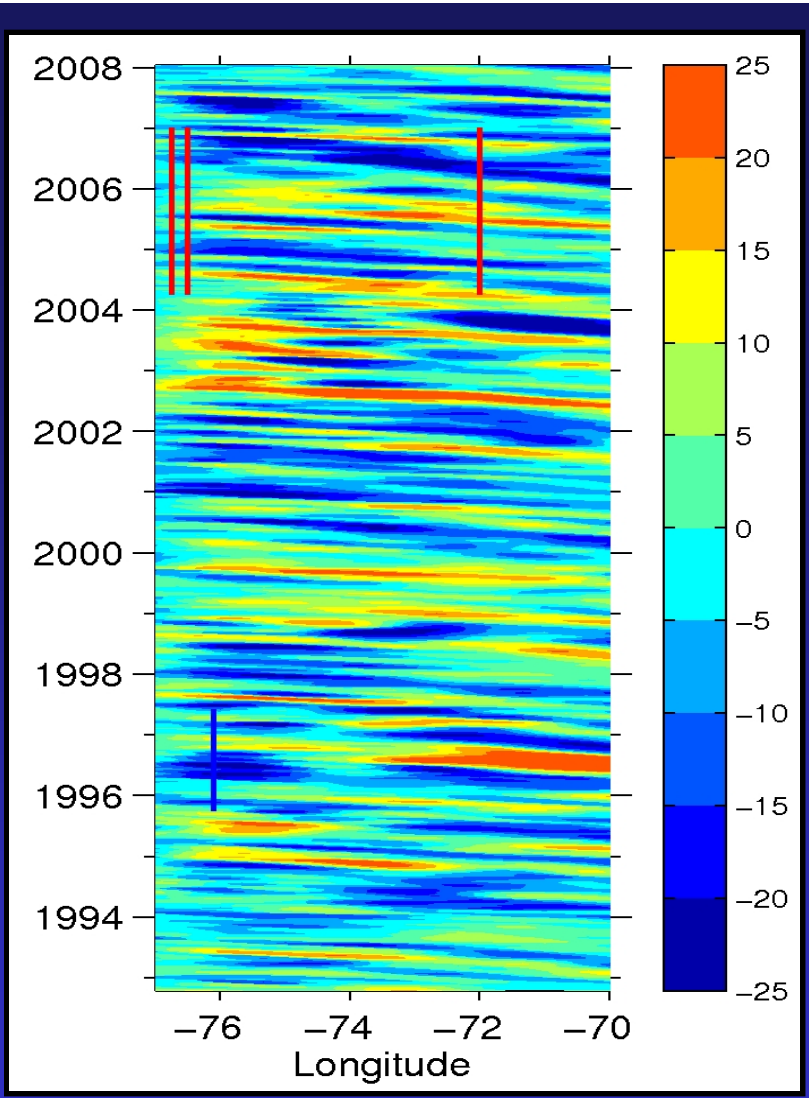
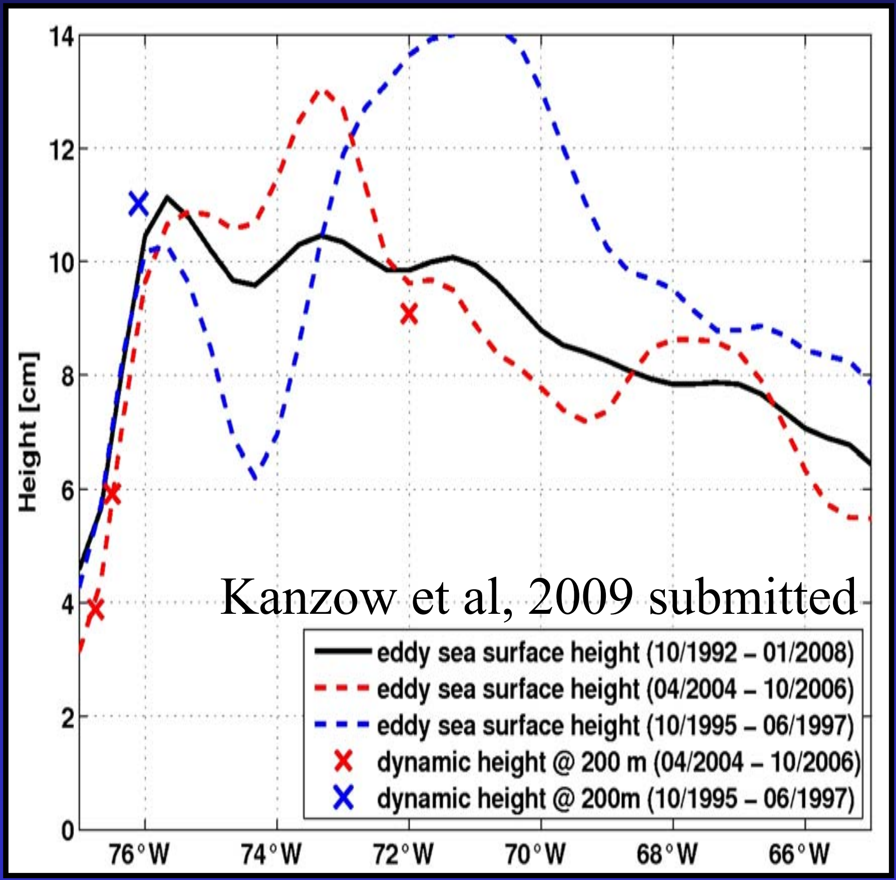
Eddies, sea-surface height, dynamic height



SSH anomaly [cm] near western boundary

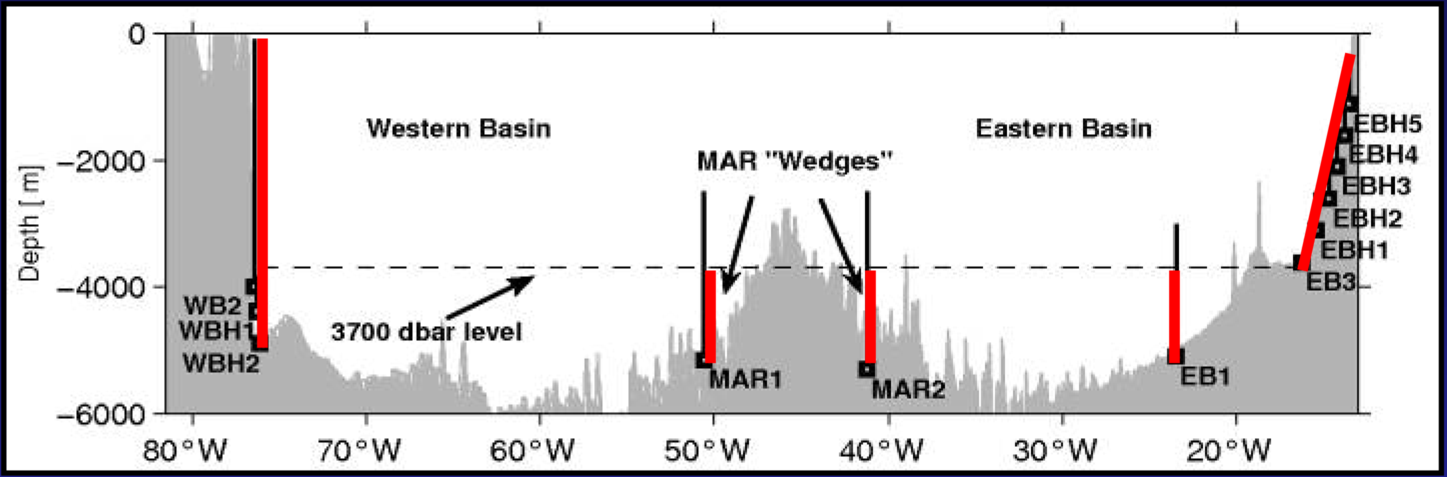


Kanzow et al, 2009 submitted

Standard deviation of SSH and dynamic height [cm]

➔SSH fluctuations increase gradually from east to west, yet decrease sharply with 100 km from the western boundary

The RAPID-MOC 26.5°N Array



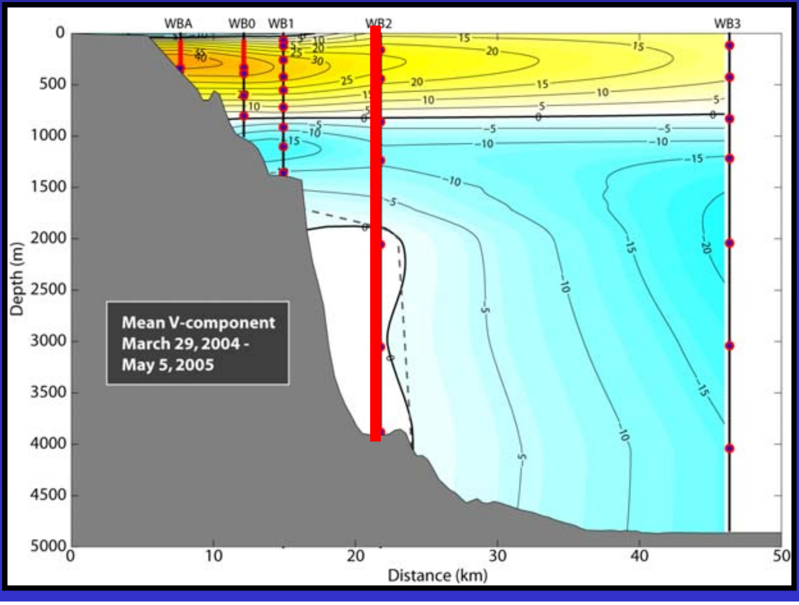
$$T_{INT}(z) = -g/(\rho f) \int_{Z_{REF}}^{0} [\rho_{EAST}(z) - \rho_{WEST}(z)] dz$$

Basin wide integrated internal transports (T_{INT}) from zonal density gradient

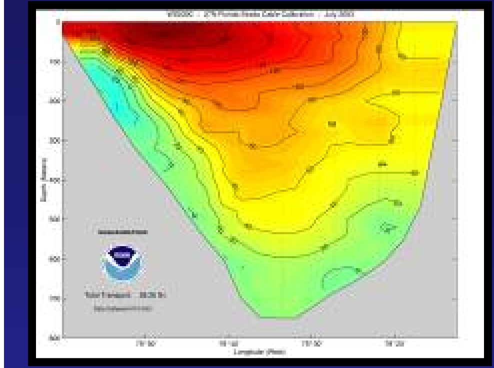
→ Funded through 2014 - will provide a 10 year time series (2004-2014)

Cunningham et al. (2007)
Kanzow et al. (2007)
Johns et al. (2008)

Transport through western boundary wedge (T_{WBW}) from current meter measurements

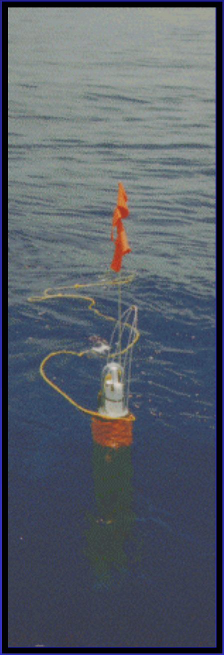


How does NOAA Contribute?



Western Boundary Time Series (WBTS) program funded by the NOAA Climate Program Office

- •Florida Current
- •Abaco Hydrography
- •DWBC transport
- •High Density XBT lines
- •Shiptime



Annual mooring recovery/deployments with ship time shared by UK/NERC, NOAA and NSF

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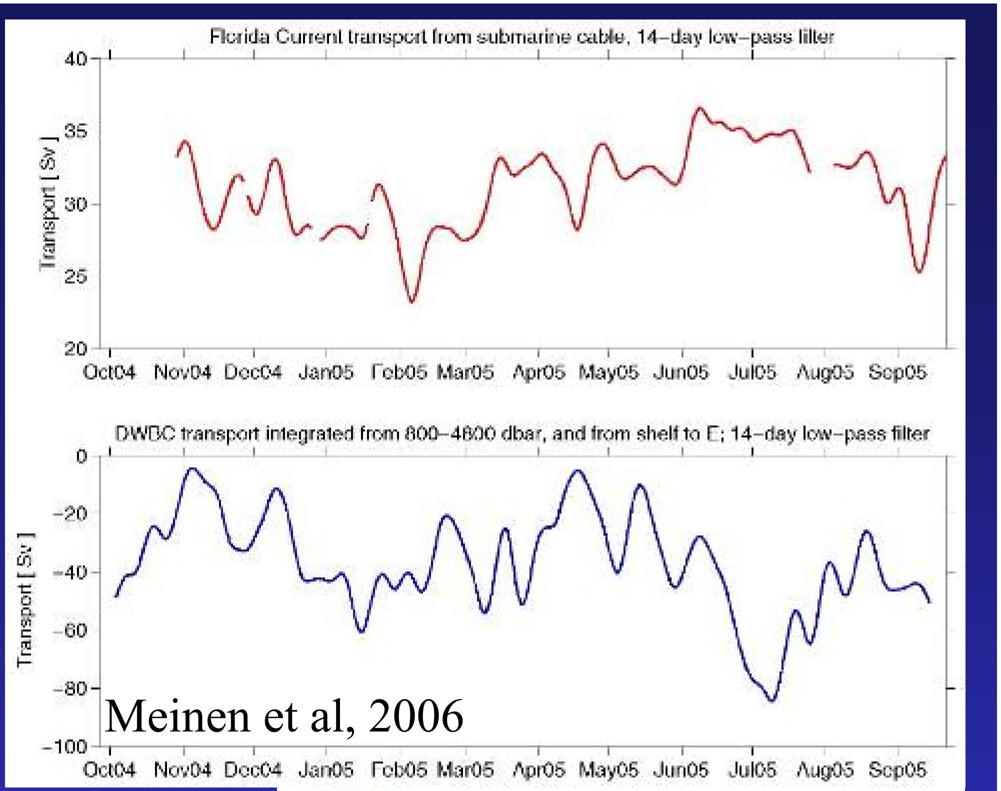
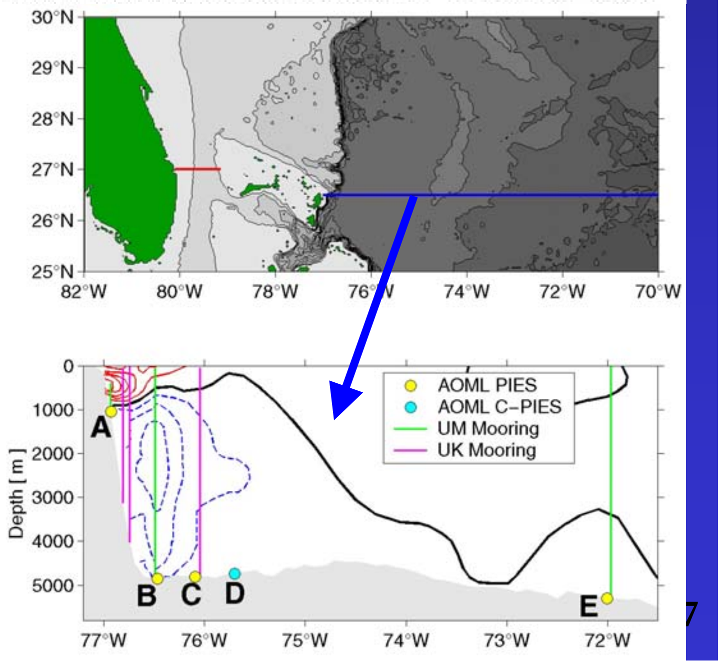
Mean Florida Current:
32 ± 1 Sv (std. err.)
Standard deviation:
3 Sv

Mean DWBC:
-37 ± 5 Sv (std. err.)
Standard deviation:
17 Sv



Meinen et al, 2006

DWBC integration is southward flow from 800-4800 dbar and from the shelf to site E (including an estimate of the bottom triangle transport west of site B).

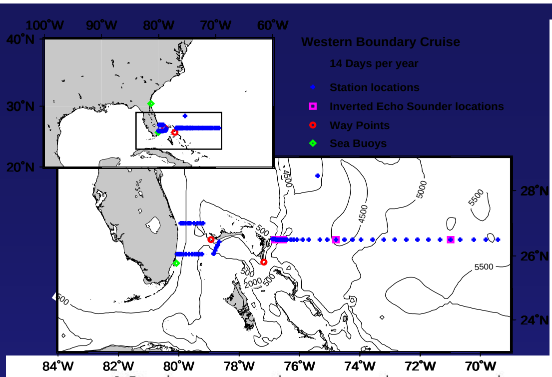


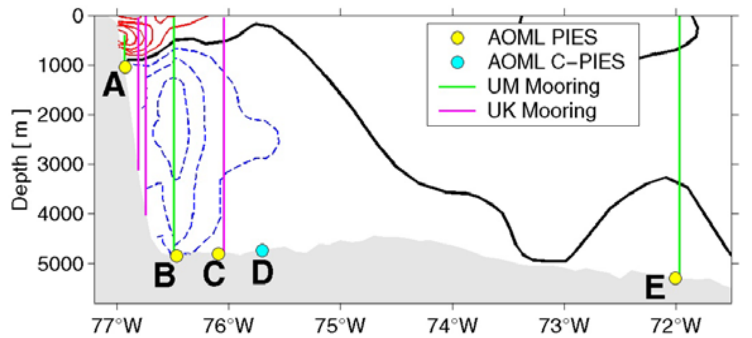
Five IES moorings added

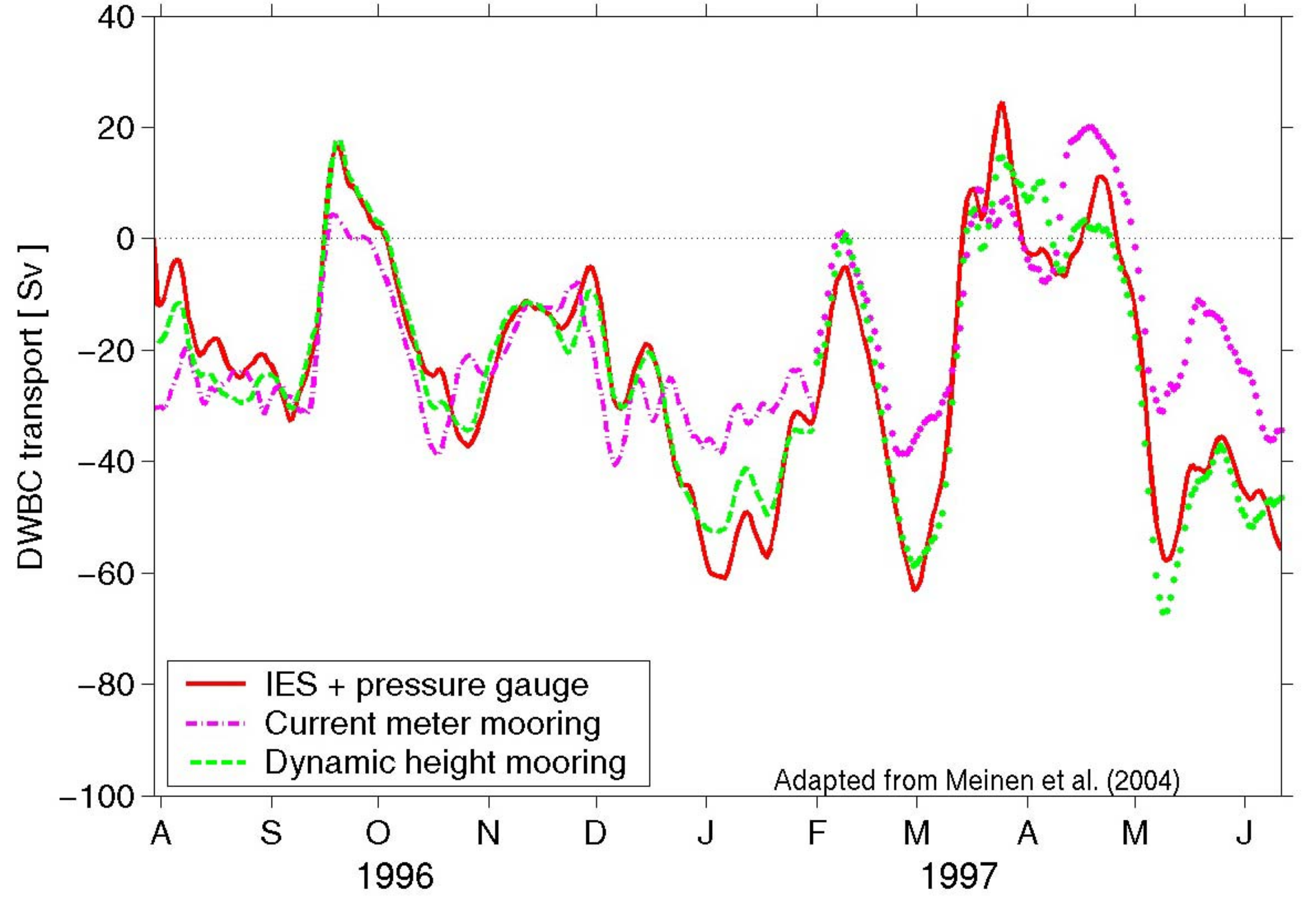
Inverted echo sounders can provide a low cost alternative to current meter moorings.

The RMS differences between the PIES and current meters
< 25% of the variability
< standard error

PIES transports agrees with “dynamic height moorings” similar to those deployed in the MOCHA/RAPID experiment.



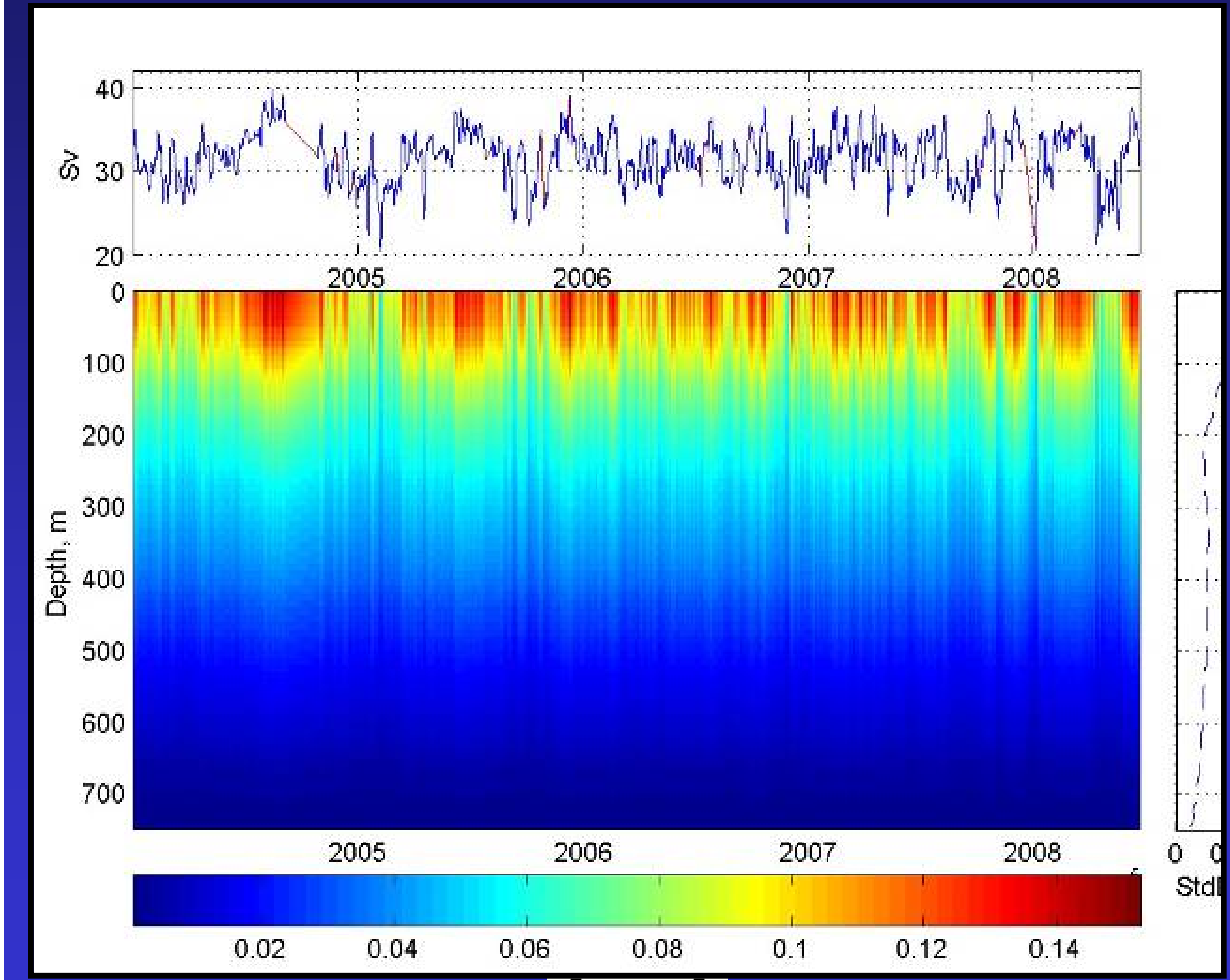




Adapted from Meinen et al. (2004)

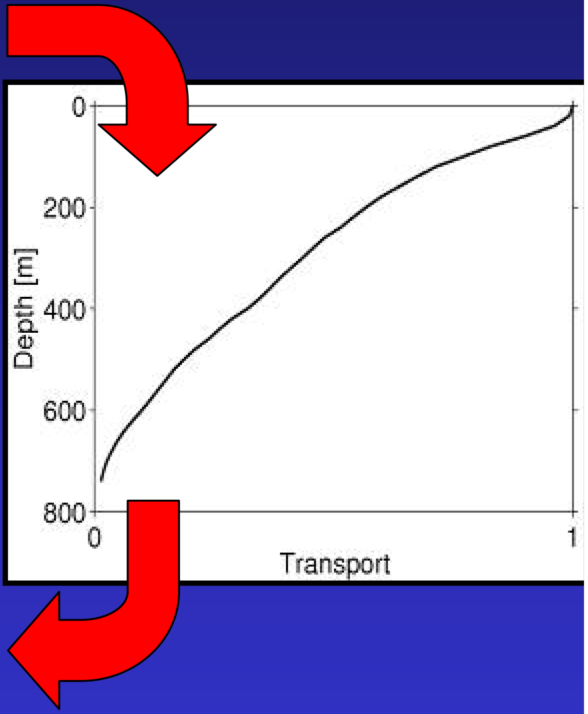
Gulf Stream Transport through the Straits of Florida: Transport profiles

Gulf Stream transport across 27oN



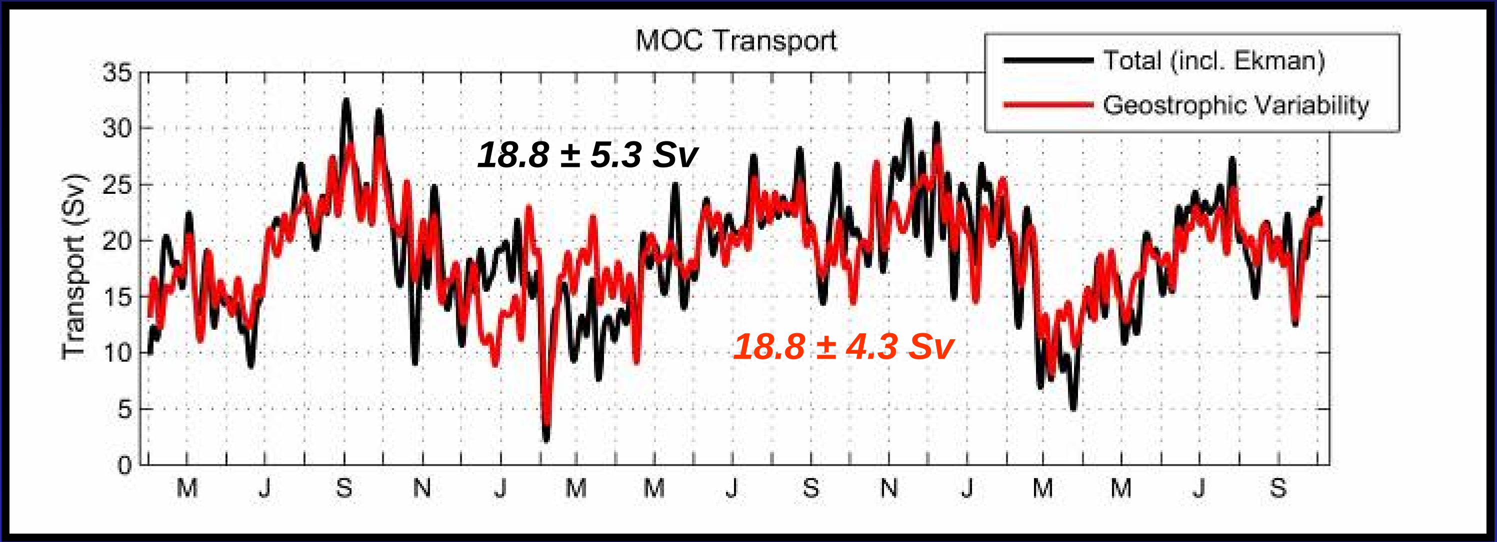
[Sv/m]

Transports [Sv] are projected on empirical vertical mode



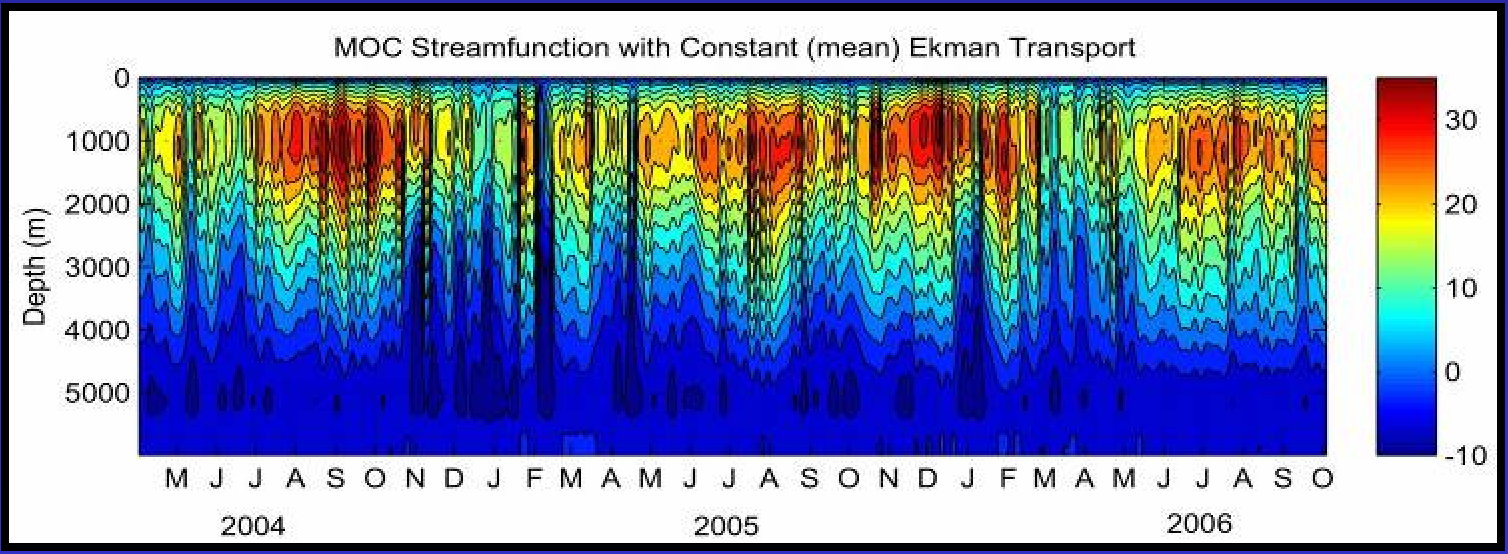
Transport per unit of depth profiles [Sv/m]

MOC Time Series 2.5 years

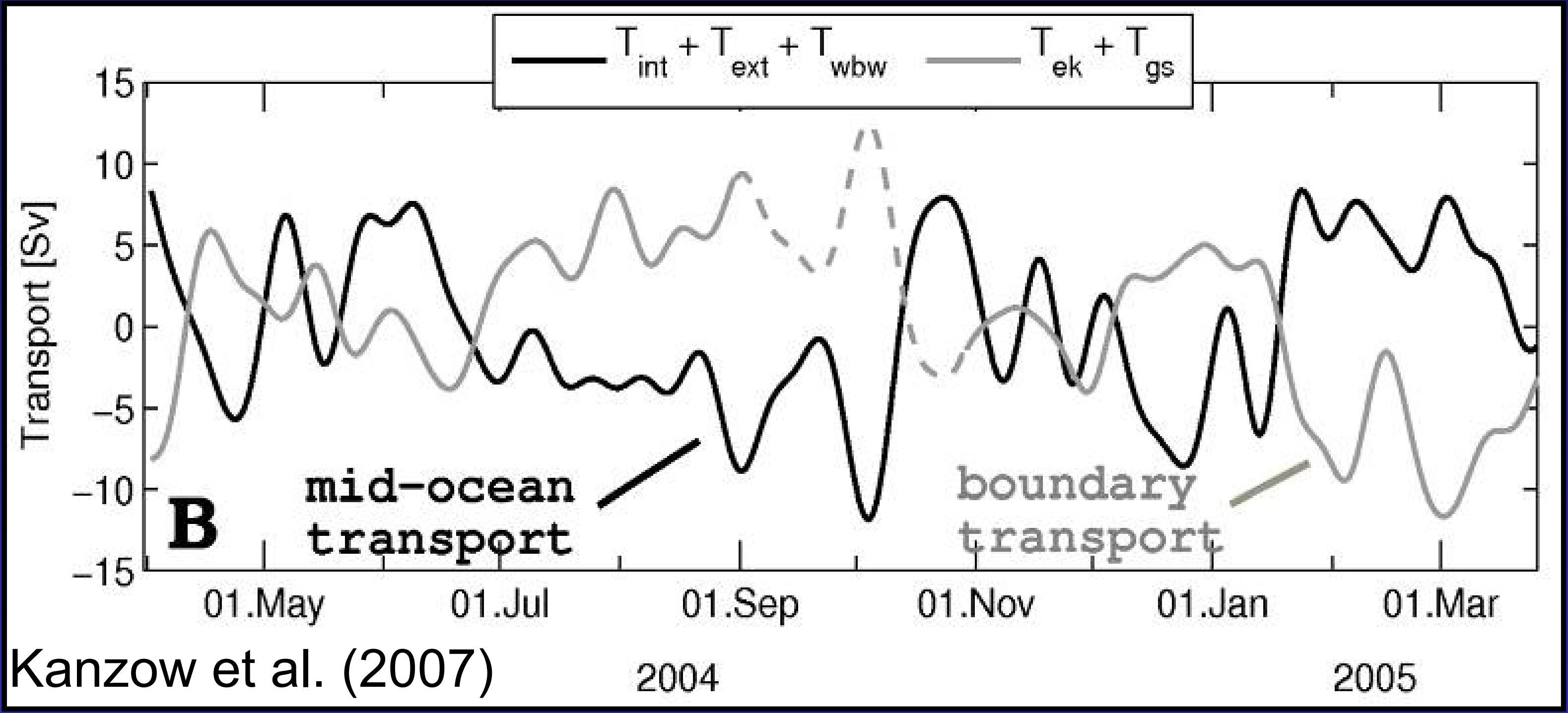


18.8 ± 5.3 Sv

18.8 ± 4.3 Sv



Transport Compensation

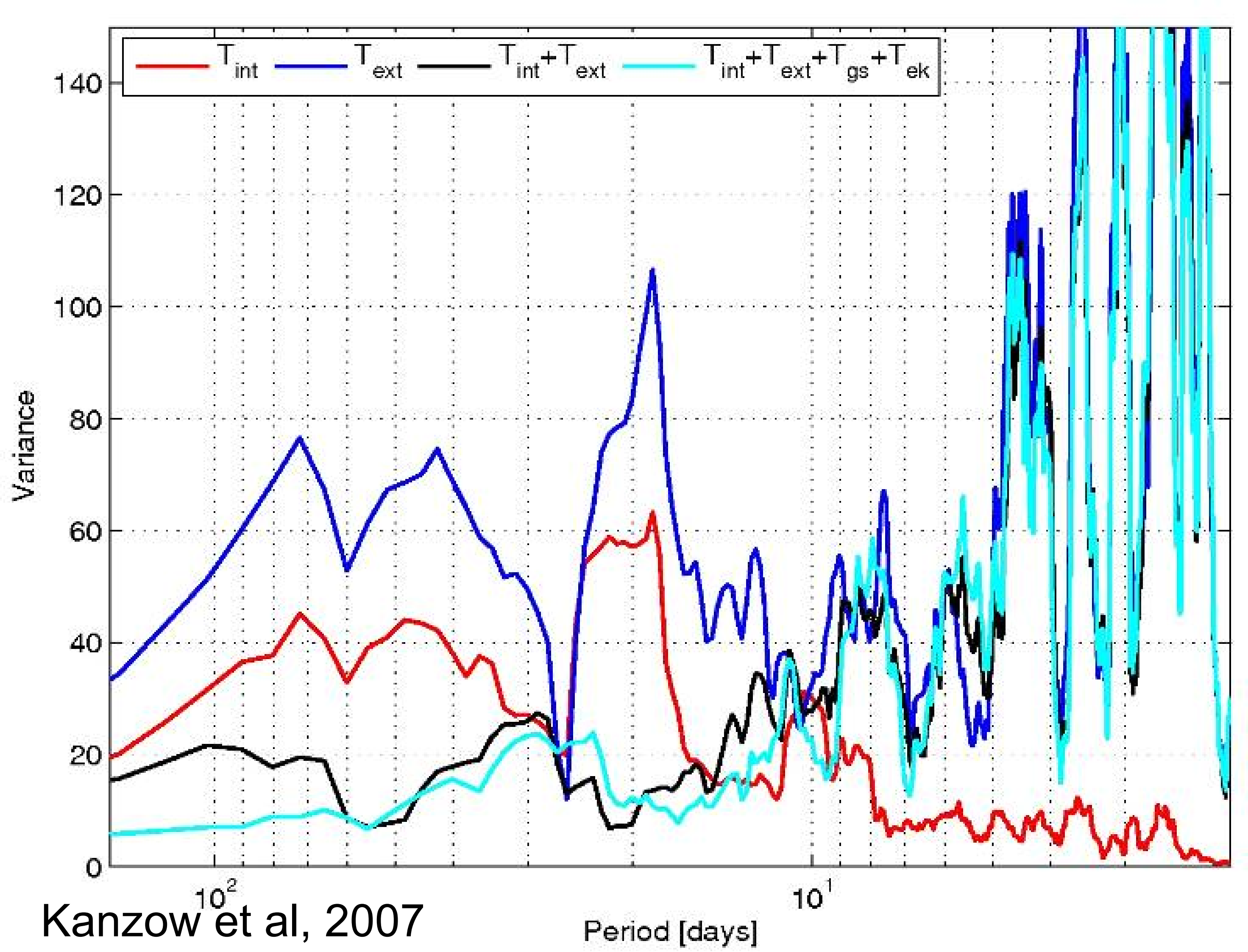


Kanzow et al. (2007)

- Mid-Ocean transport variations compensated for by Gulf Stream + Ekman transport
- Imbalance : ± 3.7 Sv

➔ Monitoring system works!!

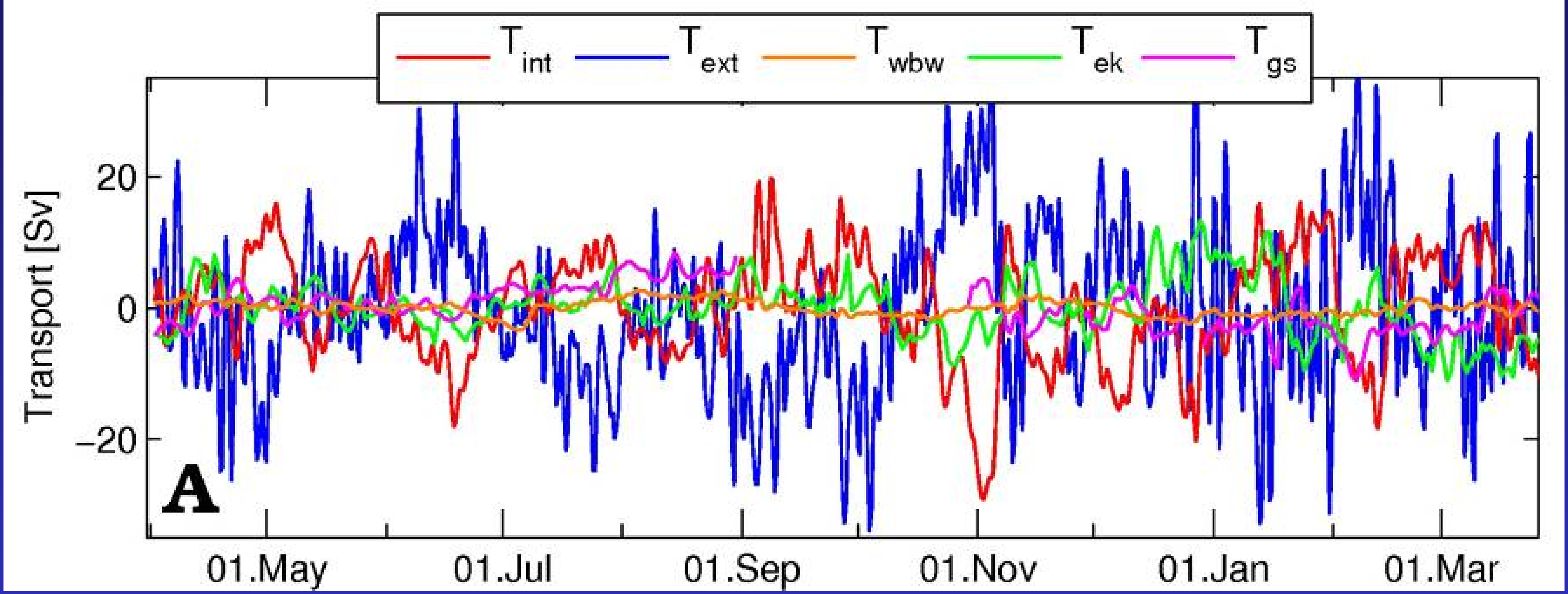
Spectra of the meridional transport fluctuations



Kanzow et al, 2007

Meridional transport fluctuations

(time mean removed)



Standard Deviation

Text: 12.6 Sv

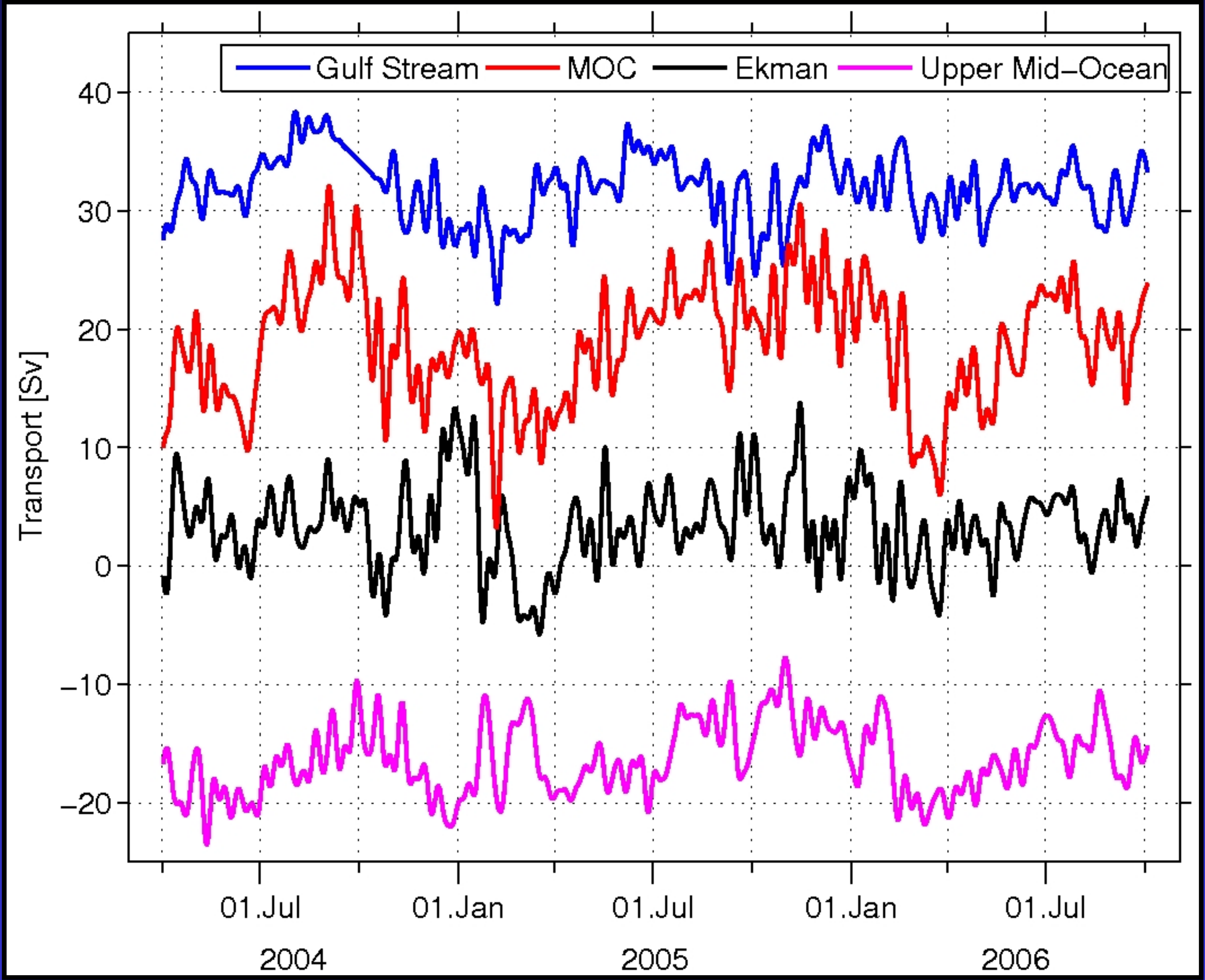
Tint : 8.3 Sv

Tek : 4.4 Sv

Tgs : 3.3 Sv

Twbw : 1.1 Sv

MOC time series



Statistics

Gulf Stream
+31.9 ± 2.8 Sv

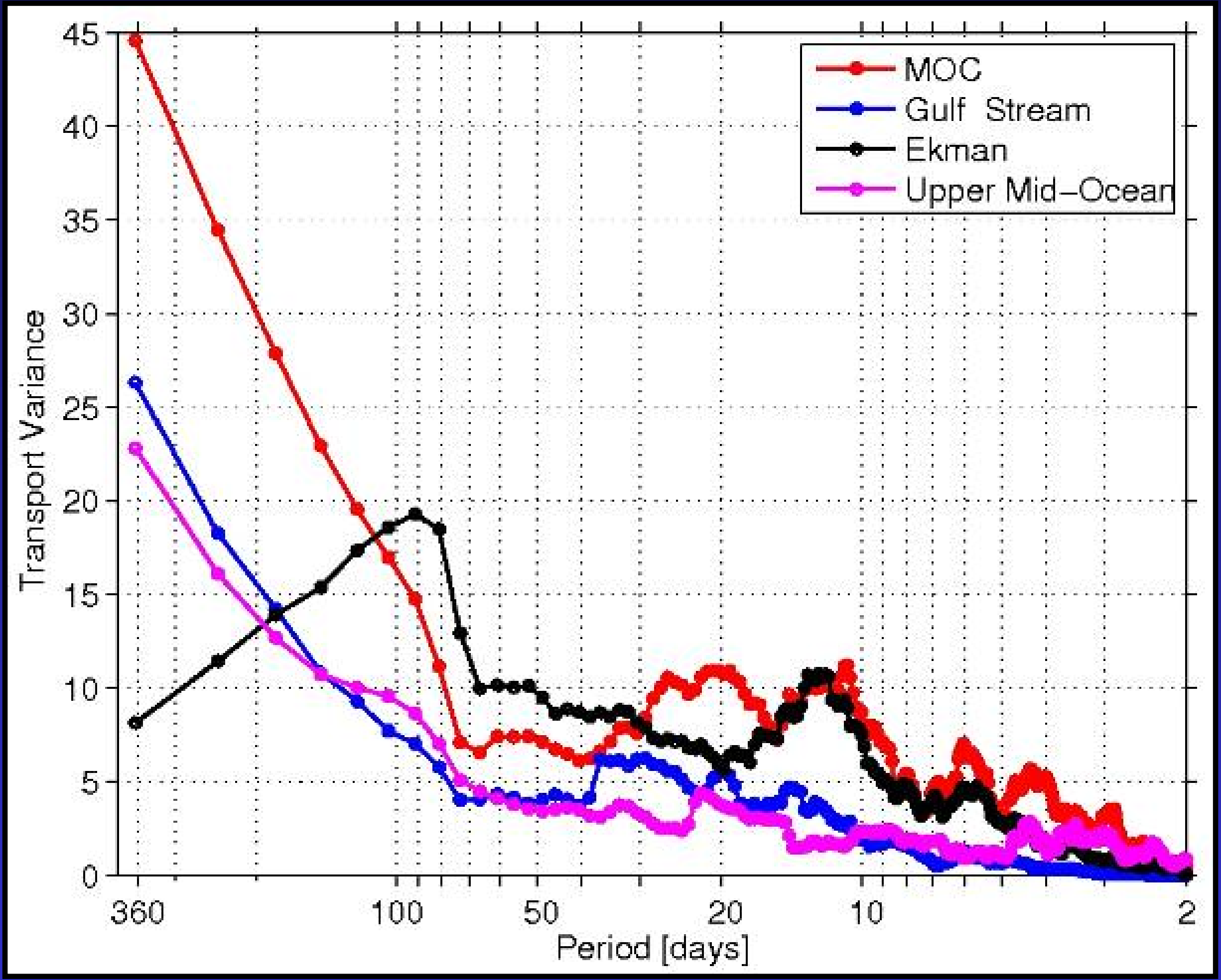
MOC
+18.8 ± 5.0 Sv

Ekman
+ 3.3 ± 3.5 Sv

Upper Mid-Ocean
-16.3 ± 3.0 Sv

Uncertainty in 2.5 year MOC mean: 1.9 Sv; assuming 18 DOF, 1.5 Sv measurement error

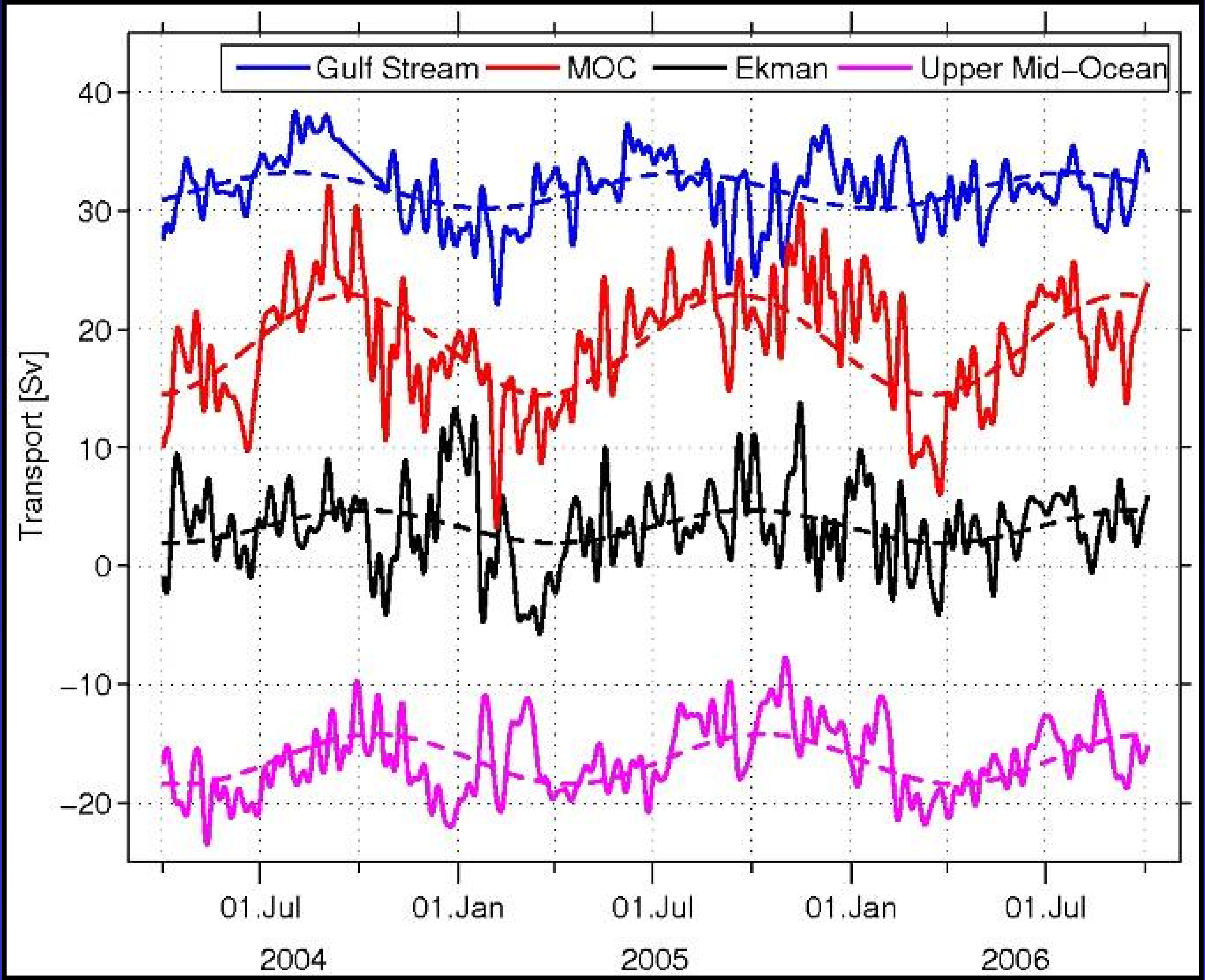
MOC Spectrum



- Ekman Transport dominates intra-seasonal variability
- Upper Mid-Ocean and Gulf Stream dominate seasonal variability

Baringer March 2009

Seasonal Variability



Seasonal Cycle

Gulf Stream
1.5 Sv (14 %)

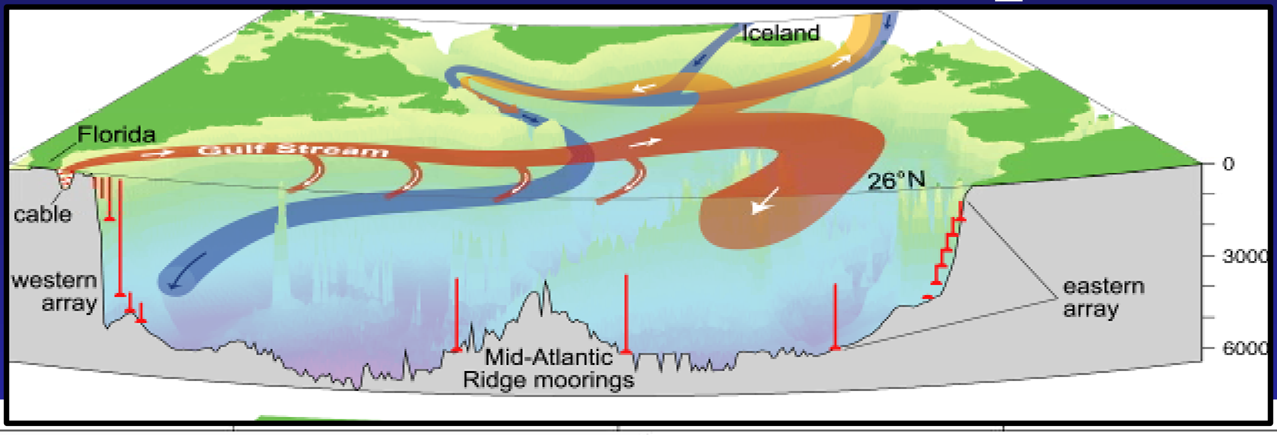
MOC
4.2 Sv (37 %)

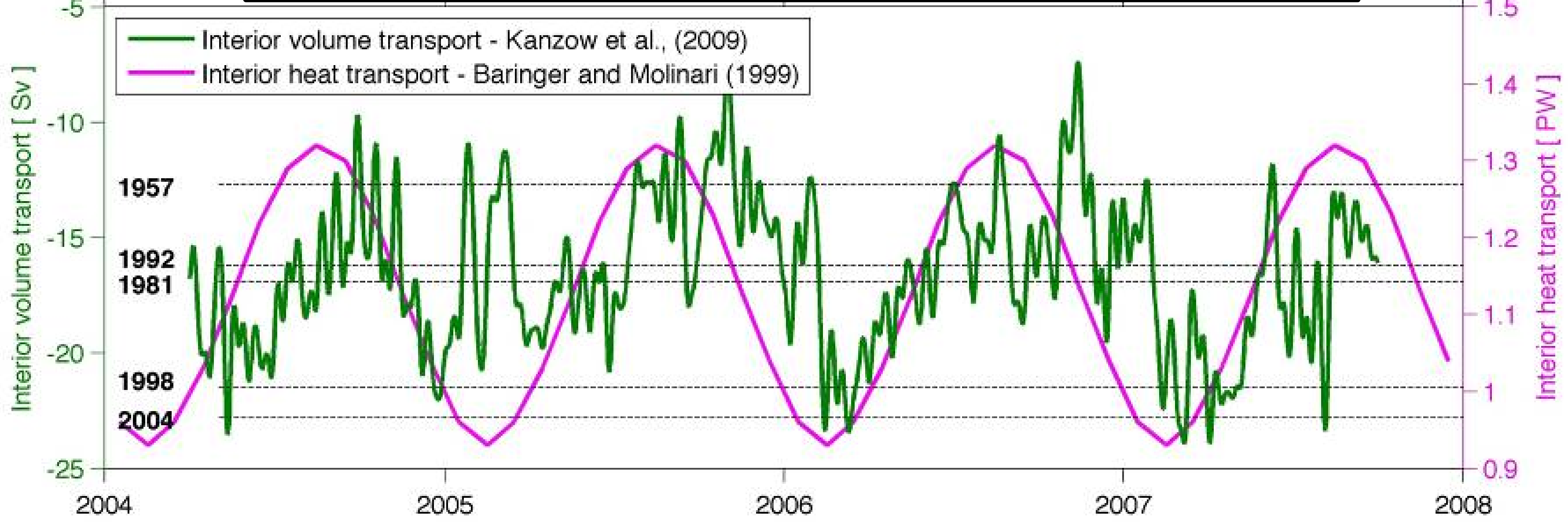
Ekman
1.4 Sv (08%)

Upper Mid-Ocean
2.1 Sv (26 %)

- MOC seasonal cycle emerging, but not significant, yet (at 5 % error probability)

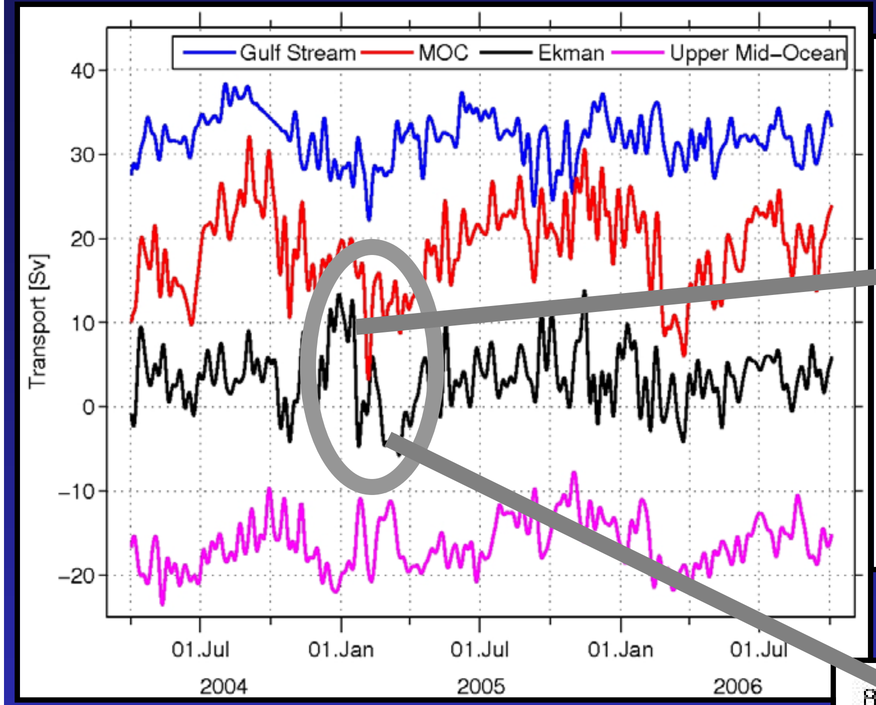
Mocha: Meridional Overturning Circulation and Heattransport Array

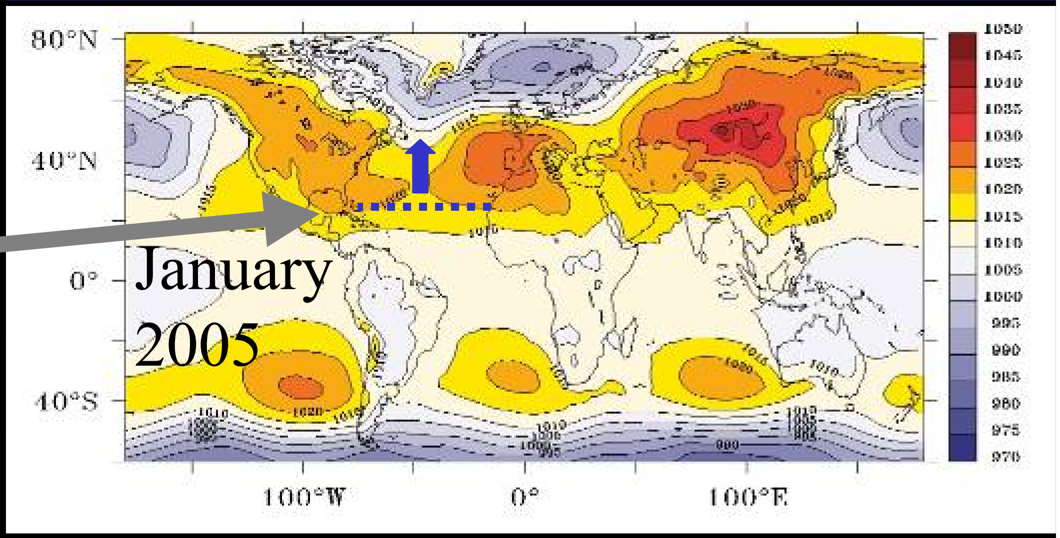


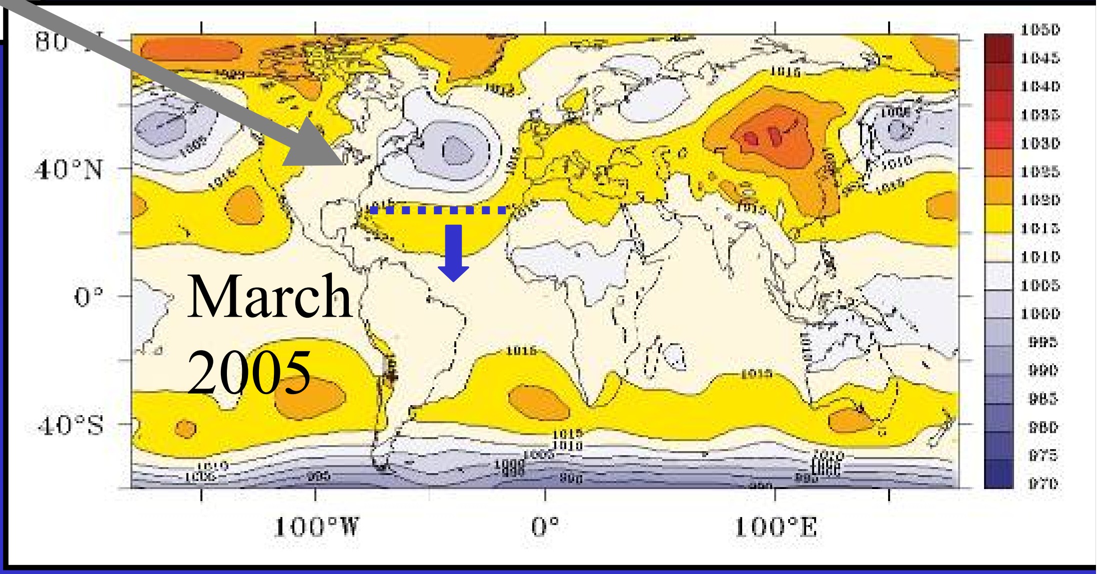


Baringer and Meinen, submitted to BAMS

MOC time series



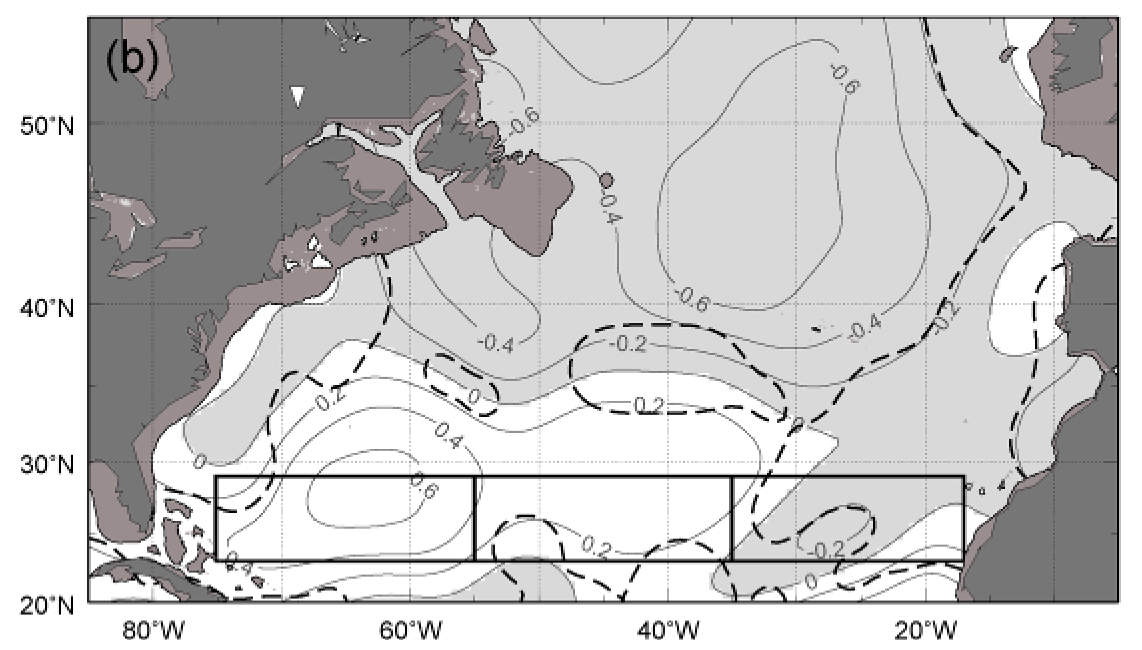




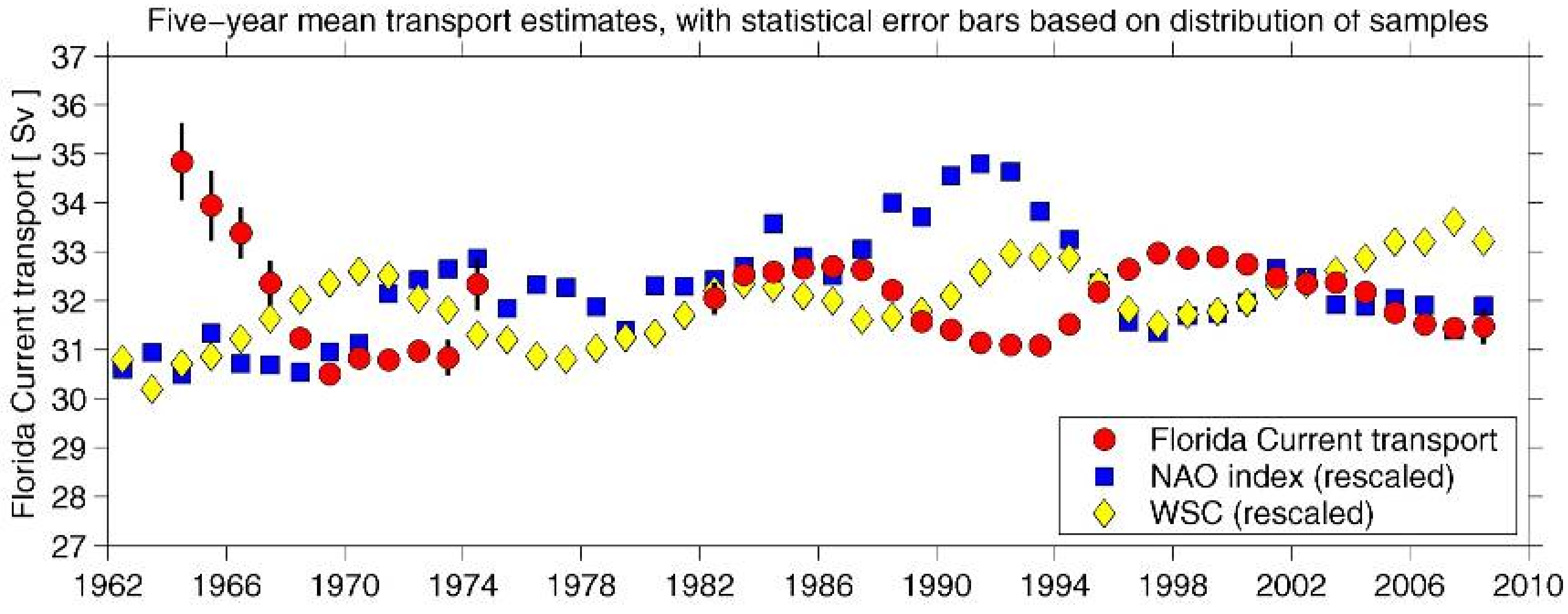
- Ekman Transport dominates intra-seasonal variability
- Upper Mid-Ocean and Gulf Stream dominate seasonal variability

Driving Florida current Variability with wind stress curl (WSC) variations

DiNezio et al, 2009, JPO.
Meinen et al, 2009, JGR, submitted



Correlation between WSC and the NAO


Five−year mean transport estimates, with statistical error bars based on distribution of samples

Heat Transport

Meridional Heat Transport: $Q_{net} = \iint \rho c_p \, v\theta \, dx \, dz$

$$Q_{net} = Q_{FC} + Q_{EK} + Q_{WB} + Q_{INT}$$

$Q_{FC} \rightarrow$ Cable voltage calibrated for temperature transport, (Shoosmith et al., 2005) $r = 0.94$, $\sigma = 0.1$ PW

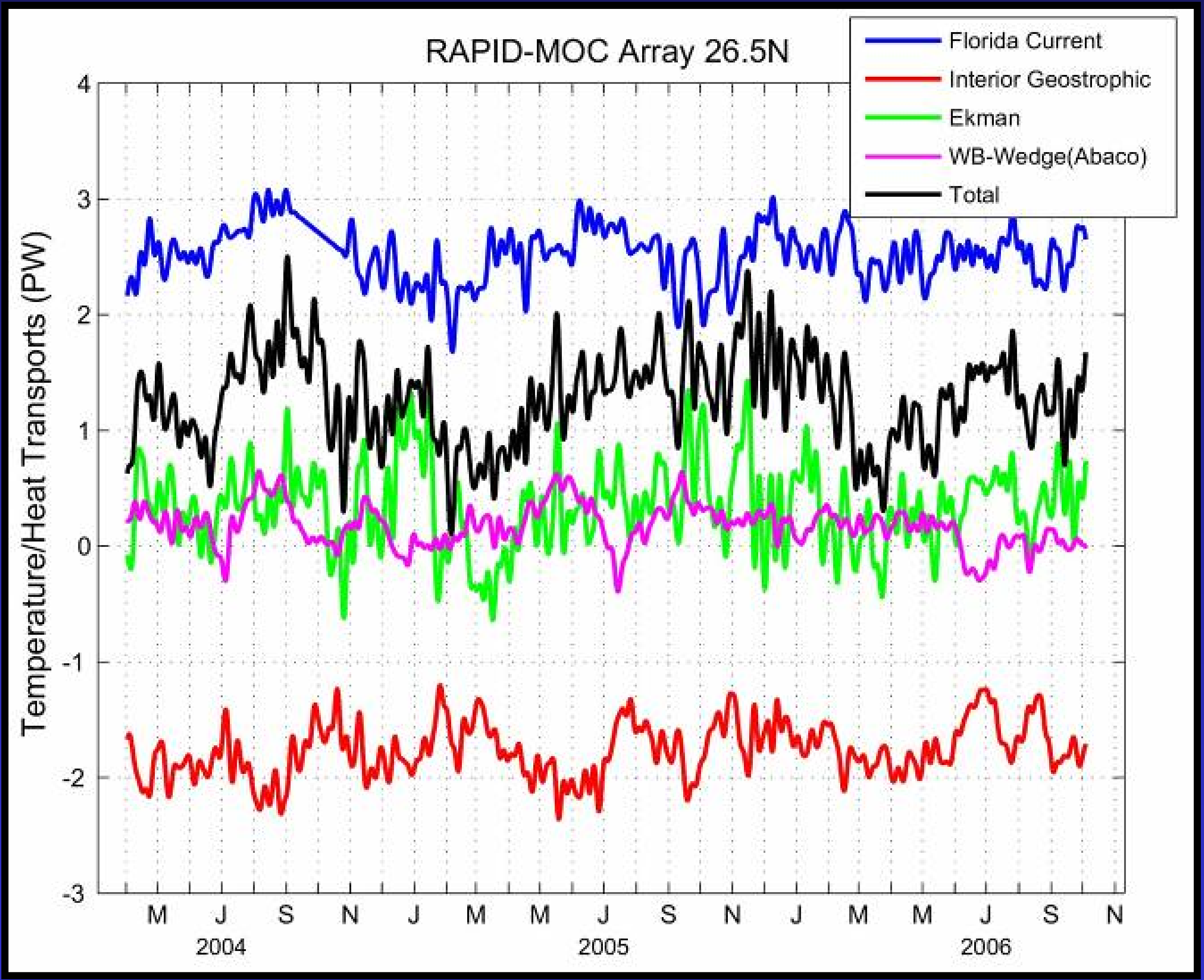
$Q_{EK} \rightarrow$ QuickScat wind stress (daily) • Reynolds SST (weekly)

$Q_{WB} \rightarrow$ Directly calculated from moored CM's/thermistors in Abaco WB array

$Q_{INT} \rightarrow$ Zonally-averaged interior transport profile from endpoint geostrophic moorings • Seasonally-averaged interior hyrdographic climatology (Hydrobase, R. Curry)

Missing: Contribution to Q_{INT} by spatially correlated v,T variability across interior: "Gyre/eddy" heat transport = $\int \int \rho c_p \, v'\theta' \, dx \, dz$

Heat Transport & Components



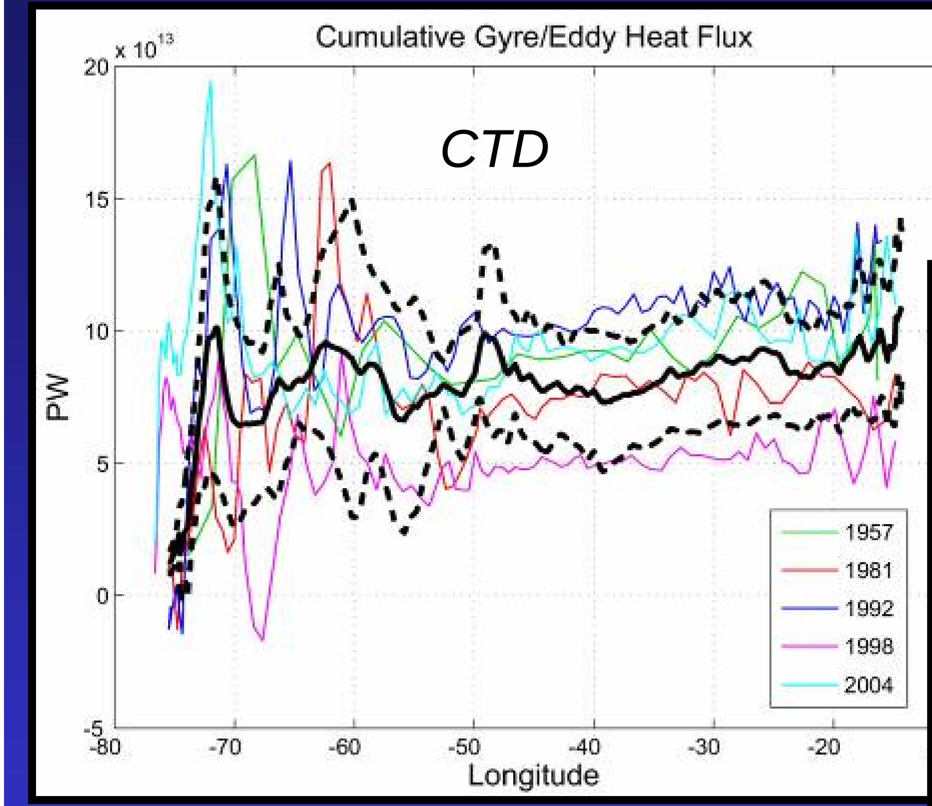
Mean MHT: 1.28 ± 0.41 PW (0.06 PW)

w/ Ekman variability removed: 1.28 ± 0.27 PW

- ➢ Ekman variability accounts for ~57% of variance

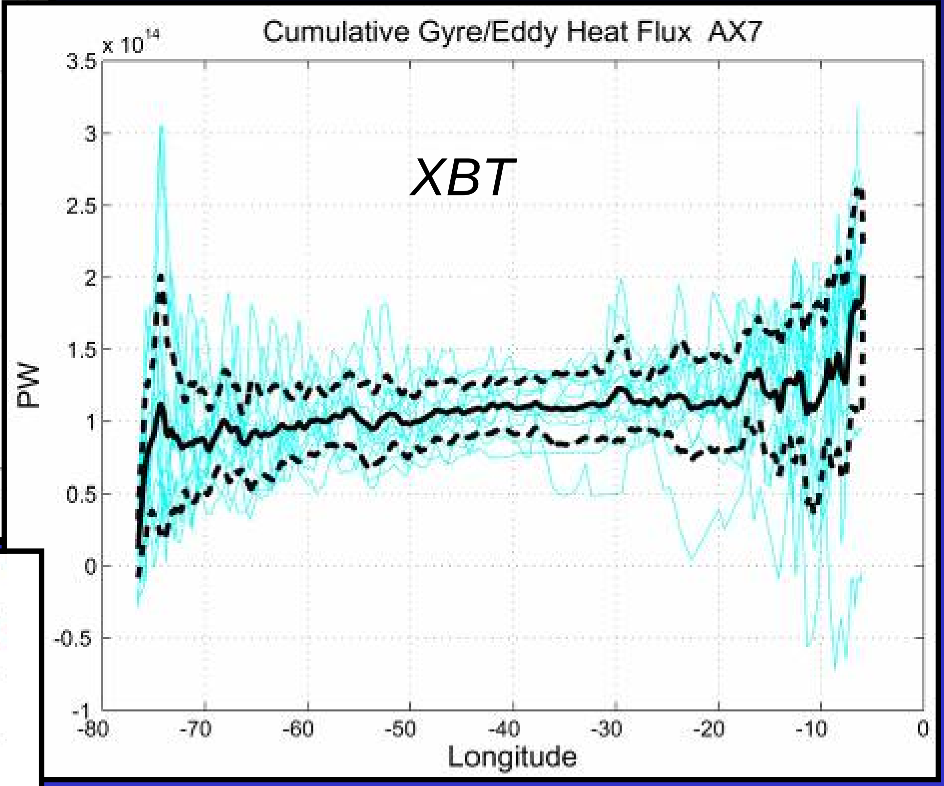
- ➢ 7-day lowpass filtered; mass-compensation time scale

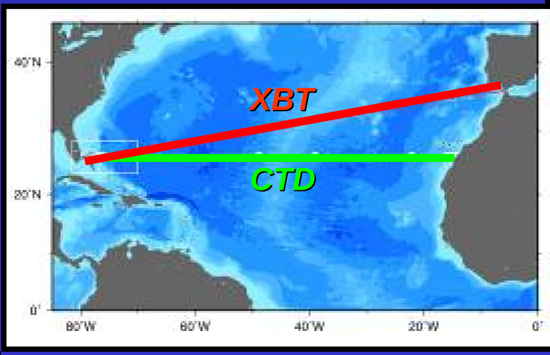
Gyre/eddy Heat Transport



$$Q_{gyre/eddy} = \int\int \rho c_p\, v'\theta'\, dx\, dz$$

$$\sim 0.10 \pm 0.03 \text{ PW}$$





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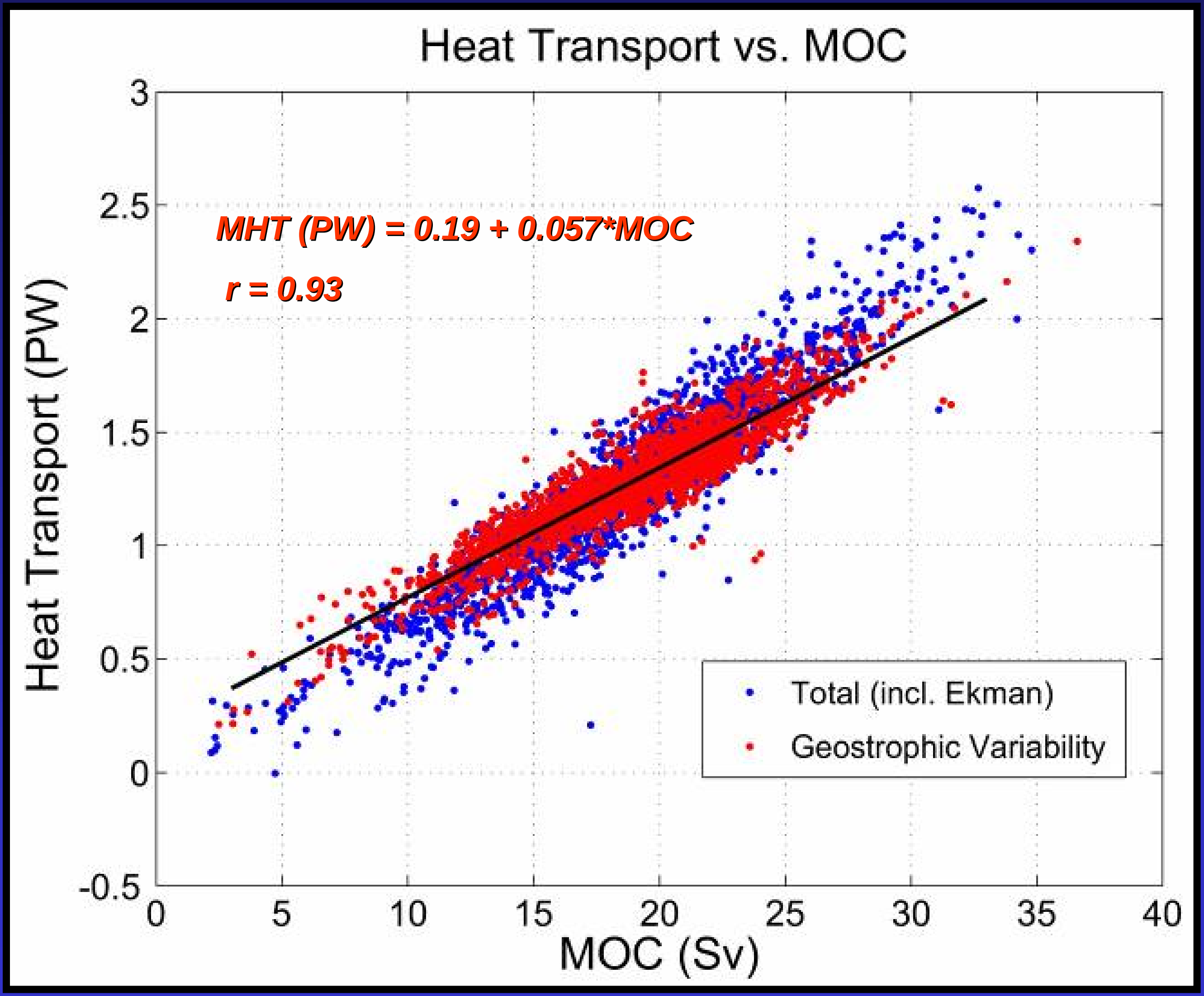
Correlation with MOC

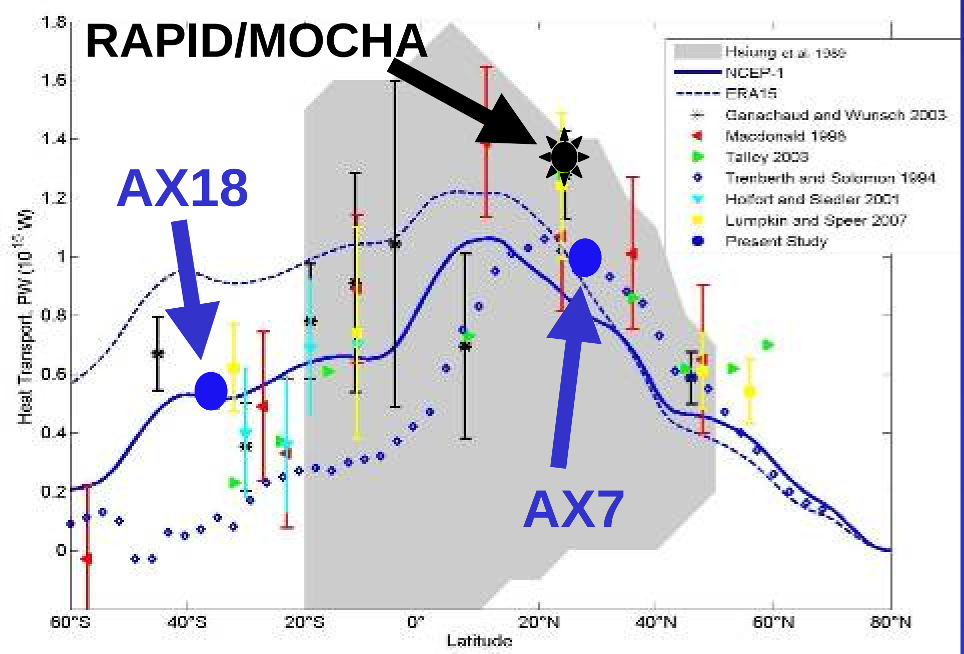


Annual Mean Heat Transport

Quantity	Mean Value	Std. error	Bias error
Q_{array}	1.26*	± 0.06	± 0.08 (?)
$Q_{gyre/eddy}$	0.10	± 0.03	-
	1.36	± 0.07	± 0.08

* deseasonalized

$$\rightarrow \; Q_{net} = 1.36 \pm 0.11 \;\; \mathrm{PW}$$



Recent Estimates at 24-26°N	MHT
Ganachaud and Wunsch (2003)	1.27 ± 0.15
Lumpkin and Speer (2007)	1.24 ± 0.25
Lavin et al. (1998)	1.27 ± 0.26
Fillenbaum et al. (1997)	1.44 ± 0.33
Molinari et al. (1990)	1.21 ± 0.34
Trenberth and Caron (2001)	1.1 (NCEP)

Conclusions

- Annual mean MOC transport = 18.8 ± 5 Sv is also slightly larger than estimates from WOCE period (16-18 Sv).

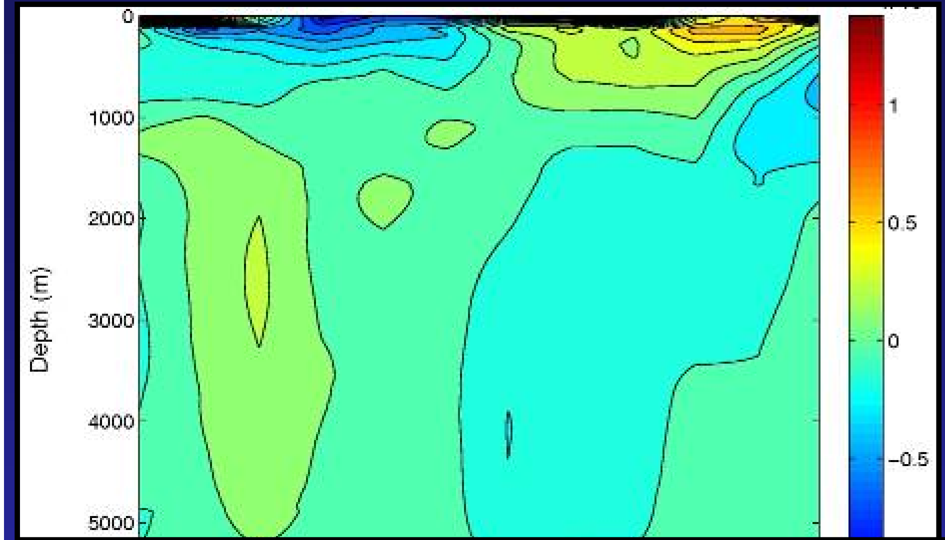
- Seasonal cycle emerging… in agreement w/ prior climatological estimates and model results. MOC dominated by FC and interior ocean while the MHT dominated by Ekman annual cycle.

- Annual mean (2004-2006) MHT across 26°N = 1.36 ± 0.11 PW. Consistent with previous direct estimates (within errors), but at upper end.

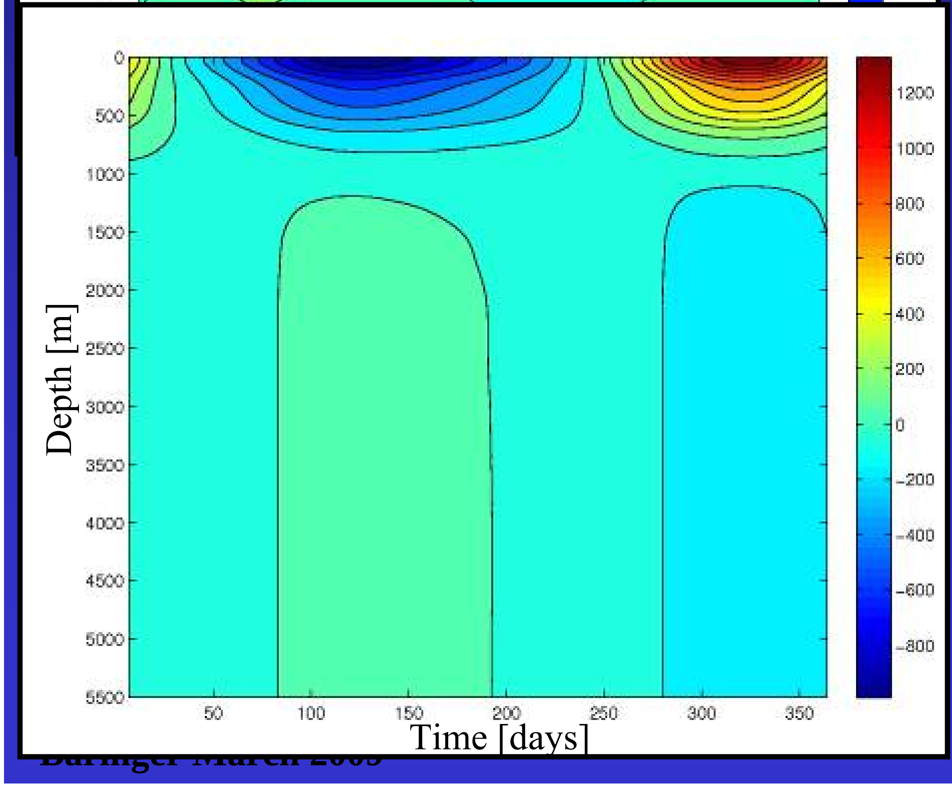
- Short term MHT variability is large. Range -> 0.1 – 2.5 PW, Std. Dev = 0.41 PW and. About half is due to Ekman transport variability, remainder due to geostrophic variability. Range of variability is consistent with eddy-permitting/eddy-resolving models, but geostrophic variability may play a bigger role than previously suggested by models (→ *Hirschi et al., 2007*)

- Mean Volume and MHT estimates from the RAPID-MOC array should provide one of the best constrained benchmarks for indirect estimates of the ocean transports (from flux climatologies, TOA radiation, etc.), and for comparison with numerical models.

Seasonal mid-ocean transport variations



Monthly averages of
mid-ocean transport profile
[$10^4\ m^2 s^{-1}$]

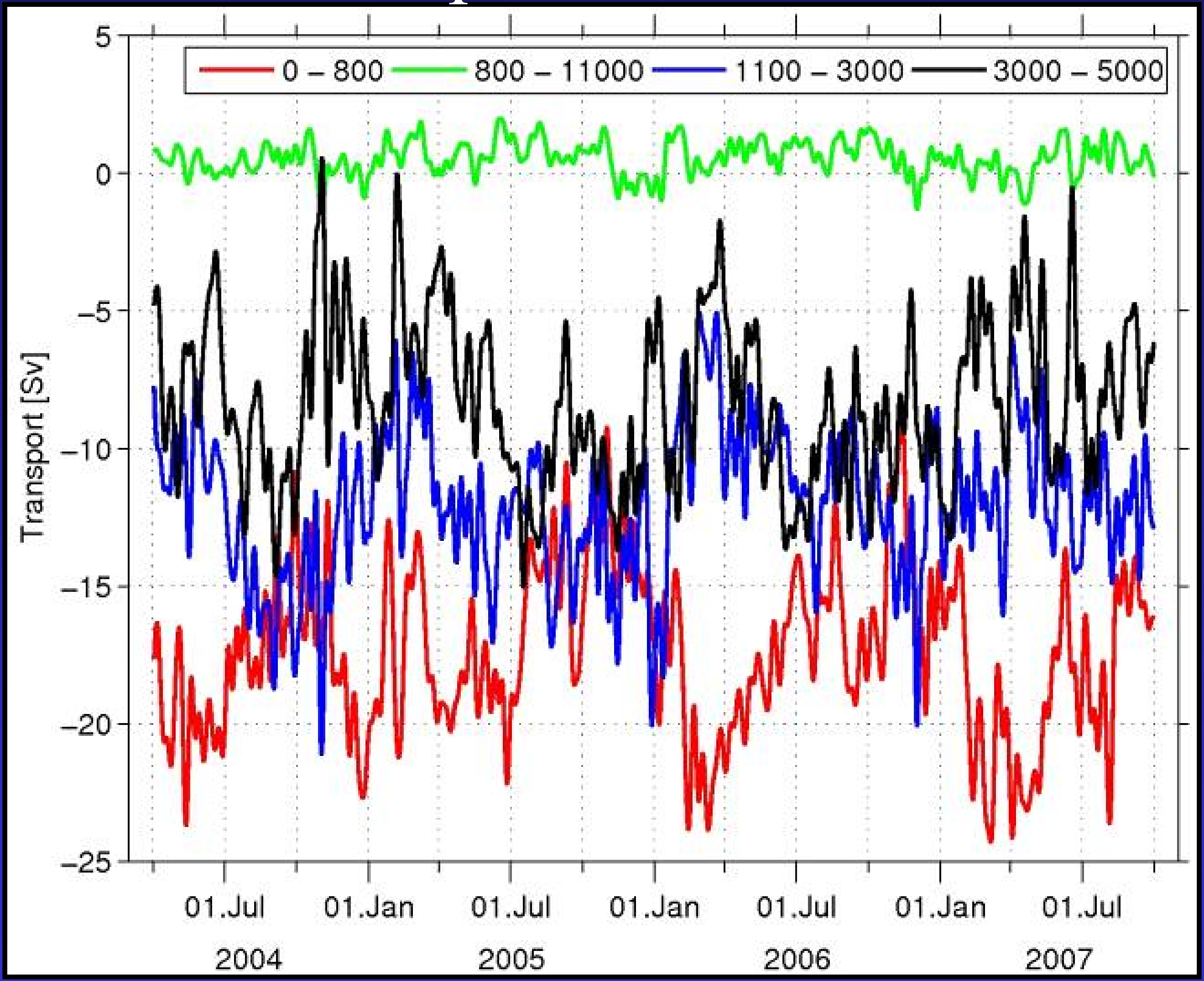


Mid-ocean transport profile from linear, forced Rossby waves (e.g. Sturges and Hong, 1995) using Seasonal cycle of wind stress curl

=>Phase agrees with observations, but amplitude too small by a factor of 4

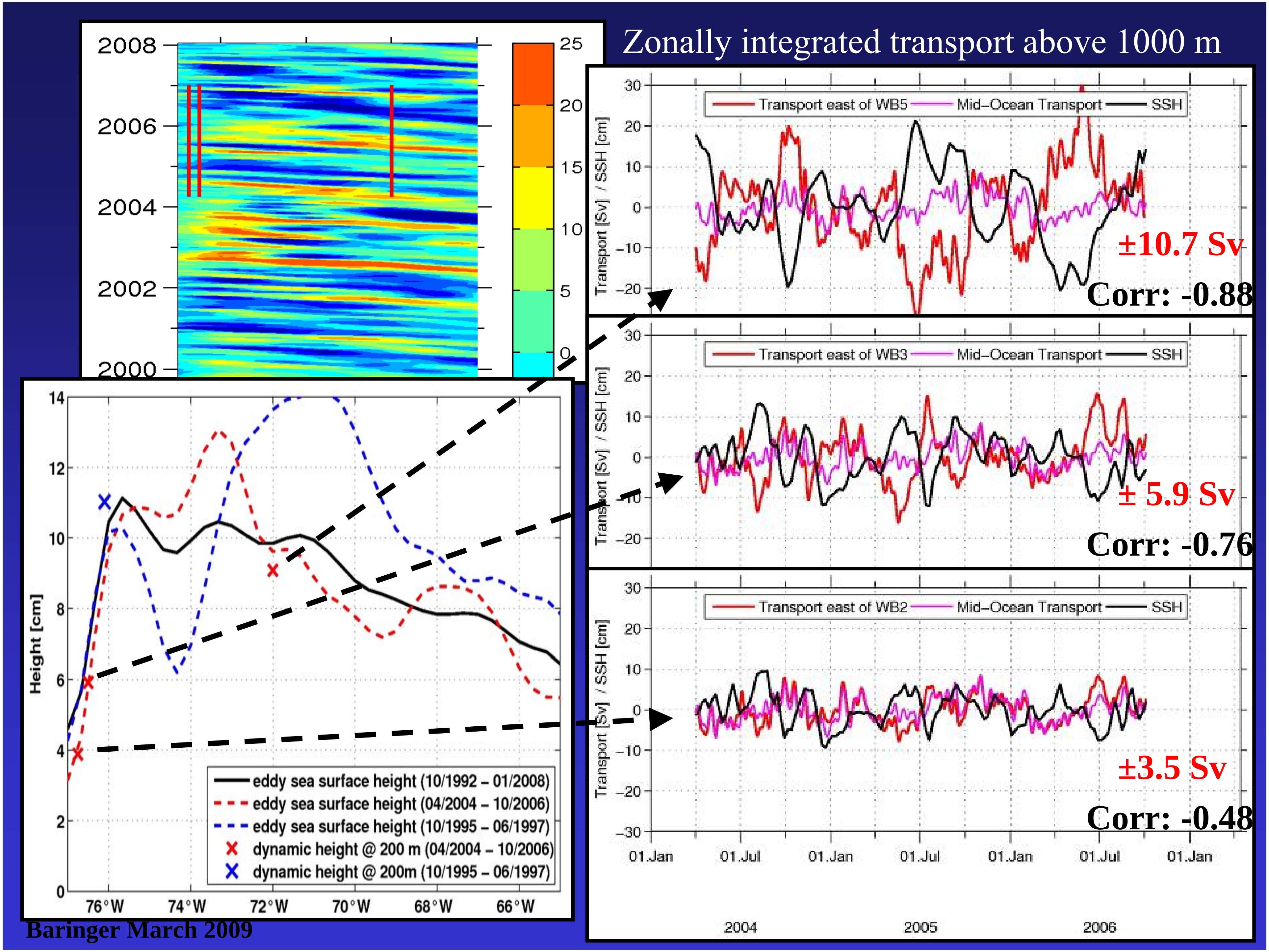
courtesy of B. Johns

Mid-Ocean transports in water mass classes



- Baroclinicity in deep water transports (where does it come from?)
- LNADW showed northward transport only once

Zonally integrated transport above 1000 m



±10.7 Sv

Corr: -0.88

± 5.9 Sv

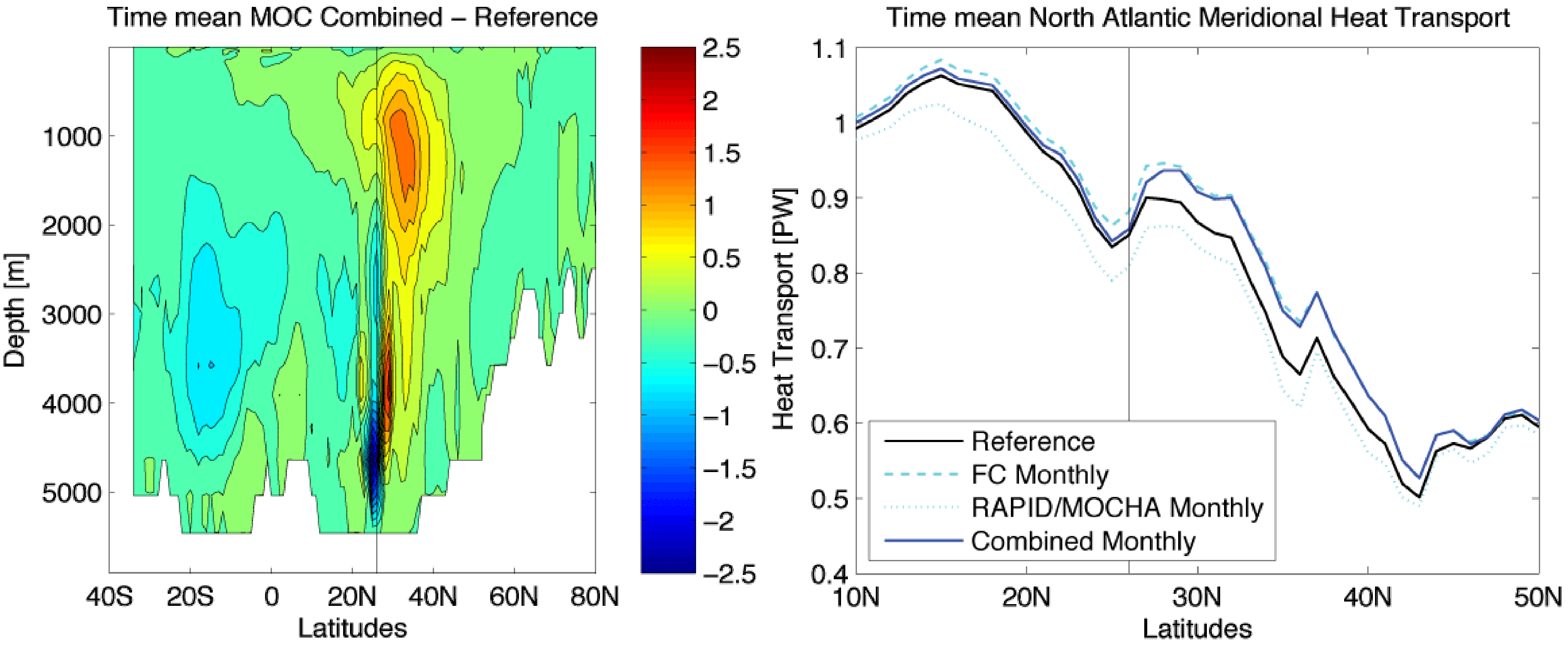
Corr: -0.76

±3.5 Sv

Corr: -0.48

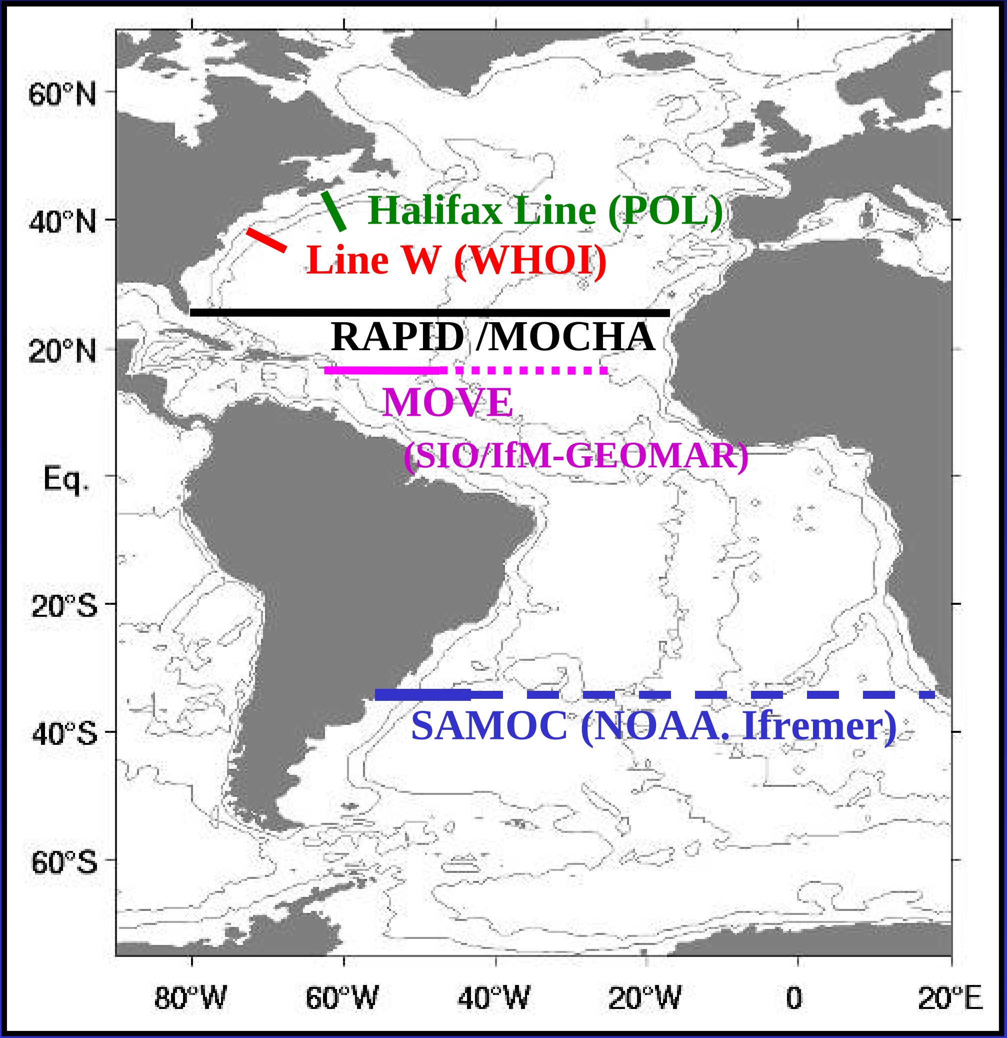
Baringer March 2009

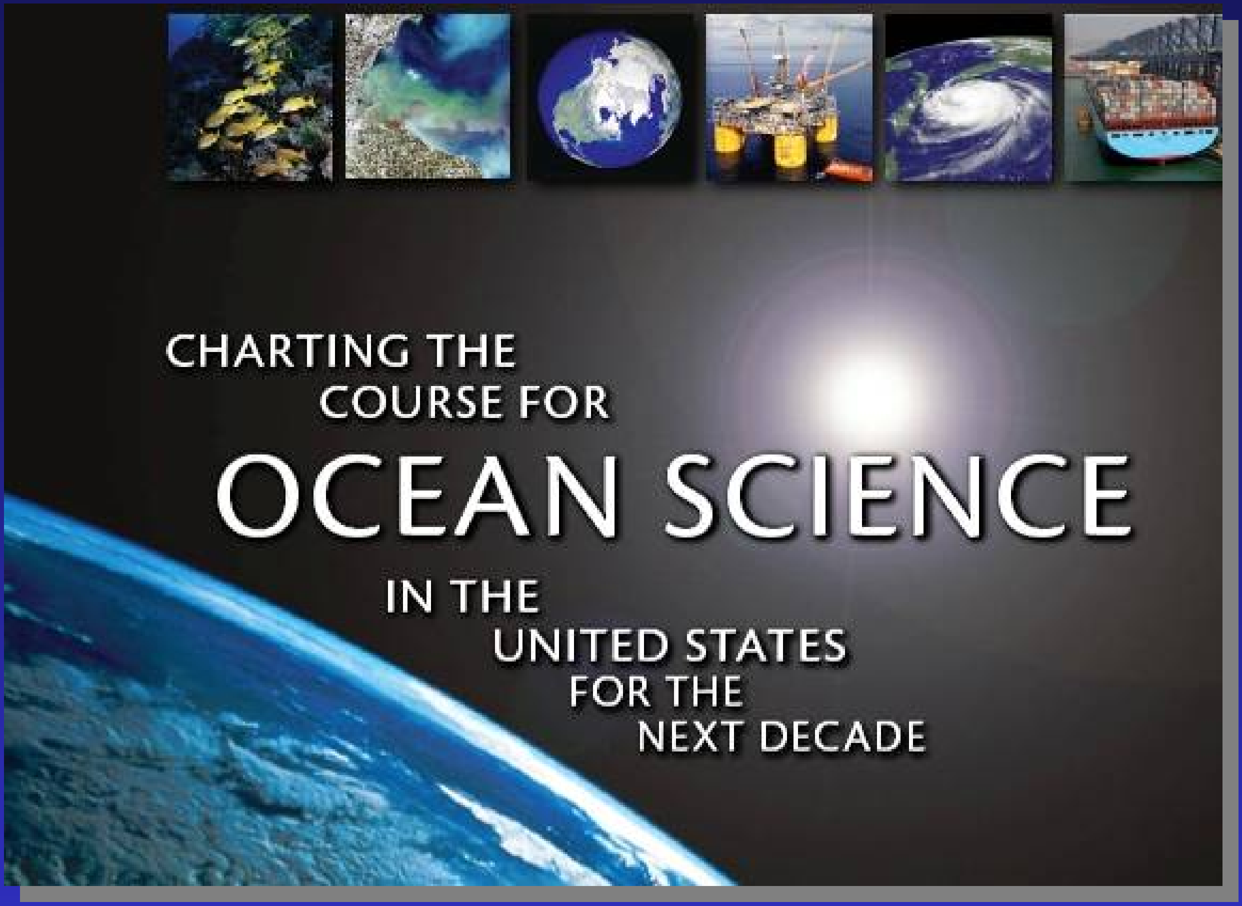
Influence of the RAPID-MOC and Gulf Stream cable measurements on the ECCO-GODAE global state estimate



J. Baehr, et al 2008, JPO, accepted

Connectivity of MOC and Deep Circulation?





CHARTING THE
COURSE FOR
OCEAN SCIENCE
IN THE
UNITED STATES
FOR THE
NEXT DECADE

The National Ocean Research Priorities Plan and Implementation Strategy presents research priorities that focus on the most compelling issues in key areas of interaction between society and the ocean.

AN OCEAN RESEARCH PRIORITIES PLAN
AND IMPLEMENTATION STRATEGY

NSTC JOINT SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY
JANUARY 26, 2007

U.S. AMOC Scientific Objectives

- The design and implementation of an AMOC monitoring system
- An assessment of AMOC's role in the global climate
- An assessment of AMOC predictability

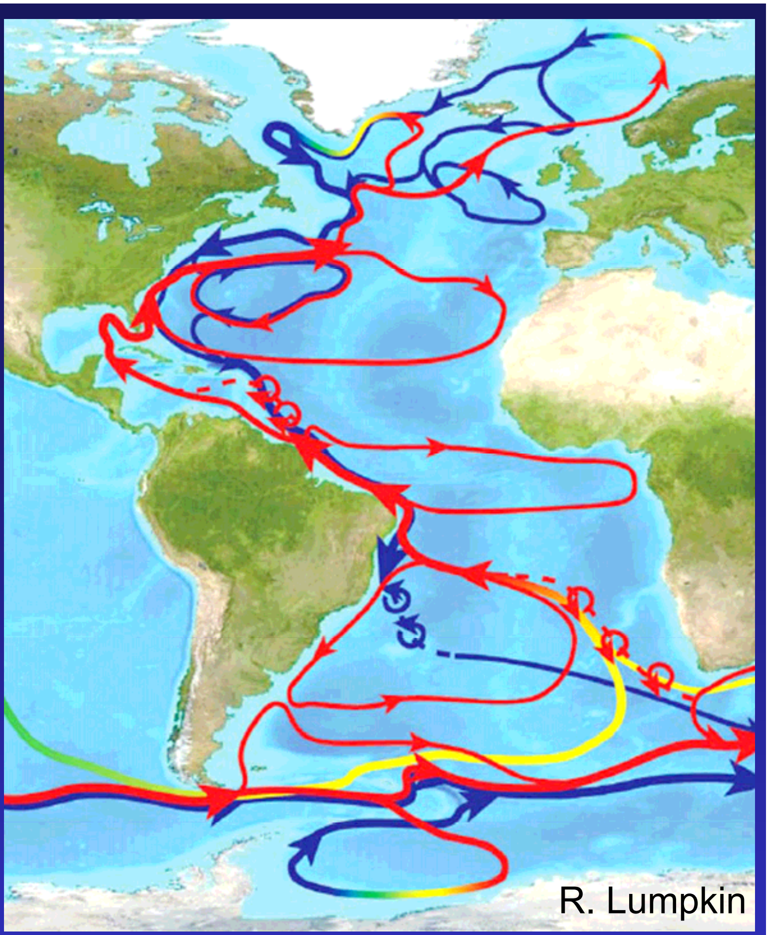
Recommended Activities

- Develop an AMOC state estimate or "fingerprint"
- Monitor AMOC transports
- Evaluate coherence and connectivity of AMOC circulation and transports
- Assess AMOC observing systems with ocean models
- Reconstruct AMOC variability and associated property fields
- Model the ocean state during the instrumental period
- Develop longer-term proxies for AMOC variability
- Diagnose mechanisms of AMOC variability and change
- Assess AMOC predictability
- Determine impact and feedback of AMOC variability
- Assess role of AMOC in producing observed changes

AMOC Open Science Meeting
May 4-6 2009, Annapolis, MD

www.atlanticmoc.org/AMOC2009.php

- What is the current state of the AMOC?
- How has the AMOC varied in the past on interannual to centennial time scales?
- What governs AMOC changes?
- Is the AMOC predictable on 10-100 year timescales?
- What are the impacts of AMOC variability and change?


R. Lumpkin

Outcomes

- What is the optimal observing system design for the AMOC?
- Is there an identifiable and measurable AMOC fingerprint that can be used to constrain the requirements for an AMOC observing system?
- Provide comments for September Ocean Obs 2009 Conference on Observing system recommendations.