What we've learned from the Atlantic Meridional Overturning Circulation (AMOC) observational network about AMOC processes and its role in weather and climate?

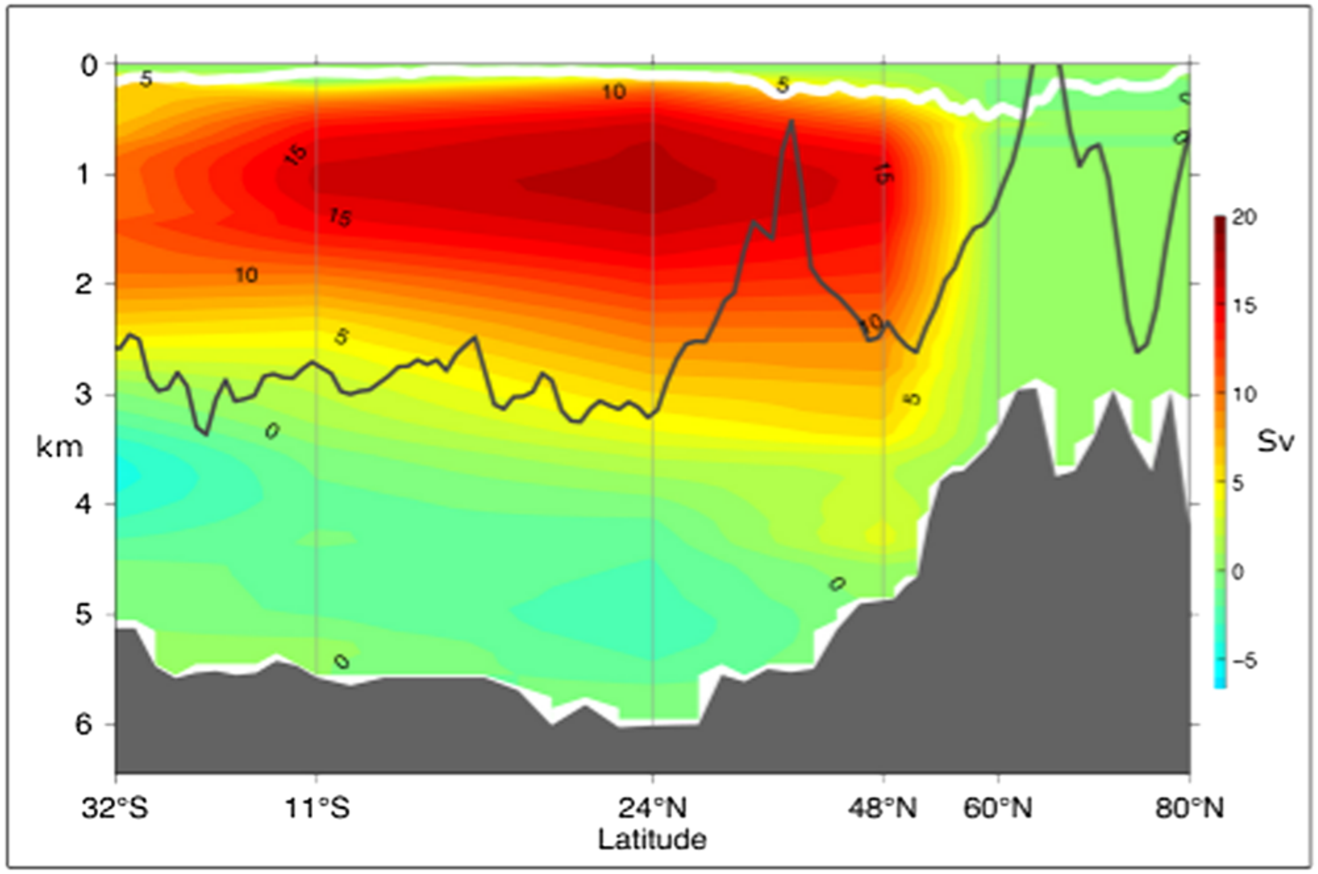
Explanations of what we've learned about AMOC processes from the past decade of AMOC observations, what gaps remain in coverage and/or what are outstanding questions that remain.

Shane Elipot
2017 US CLIVAR Summit

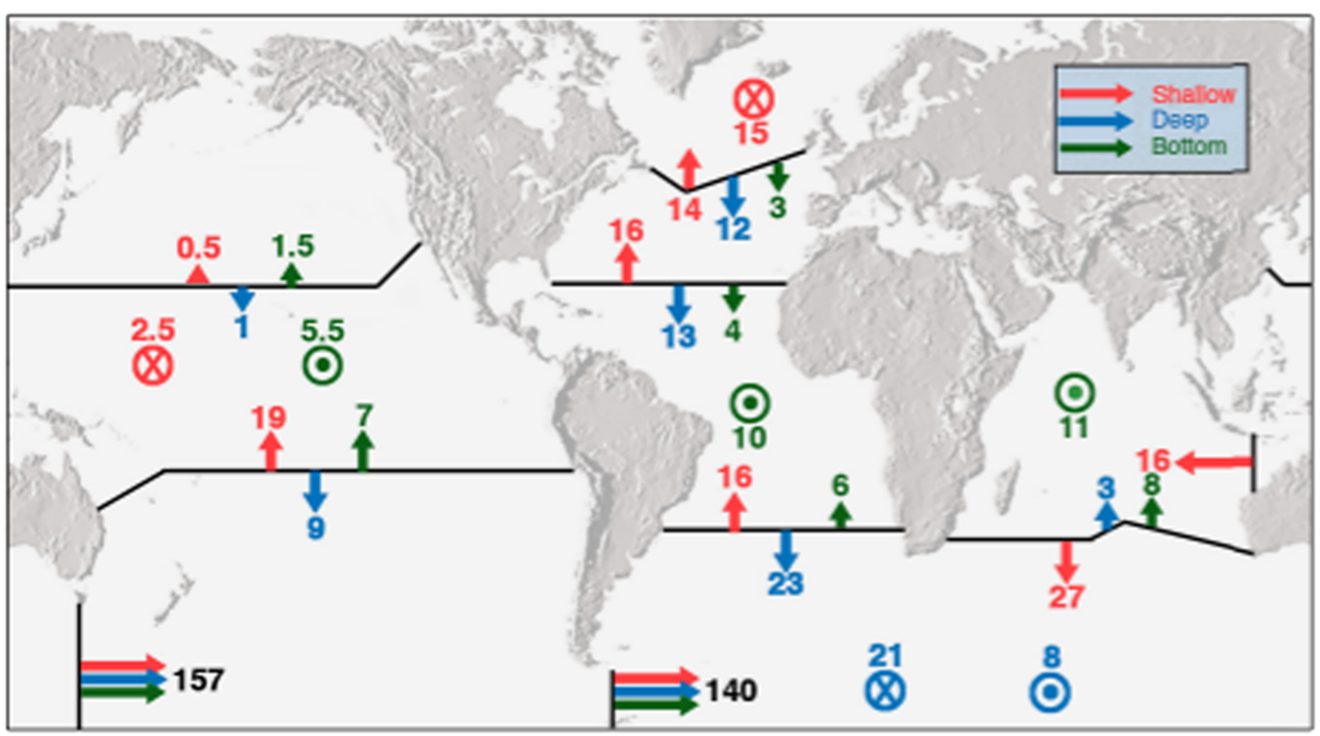
AMOC Processes

3D+1 AMOC Processes

a)



b)



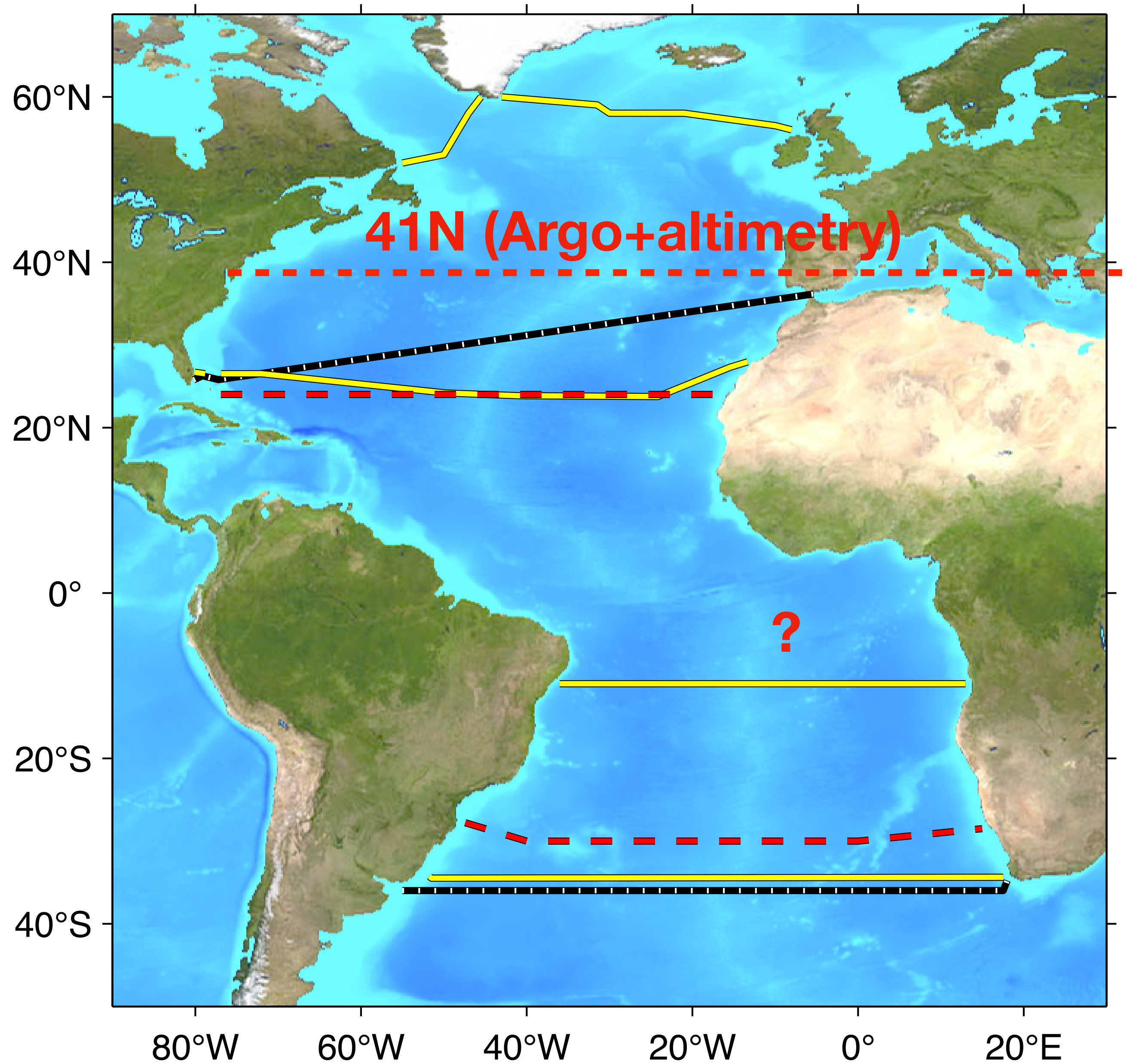
Buckley and Marshall 2016

a) Mean Atlantic Meridional Overturning stream function (AMOC) in depth coordinates estimated from tracer inversion by *Lumpkin and Speer* [[5]]. Grey shading indicates the ocean bottom (maximum depth in the Atlantic at each latitude), and the black line indicates the crest of the Mid-Atlantic Ridge. The thick white line near the surface represents the deepest (climatological) mixed layer depth.

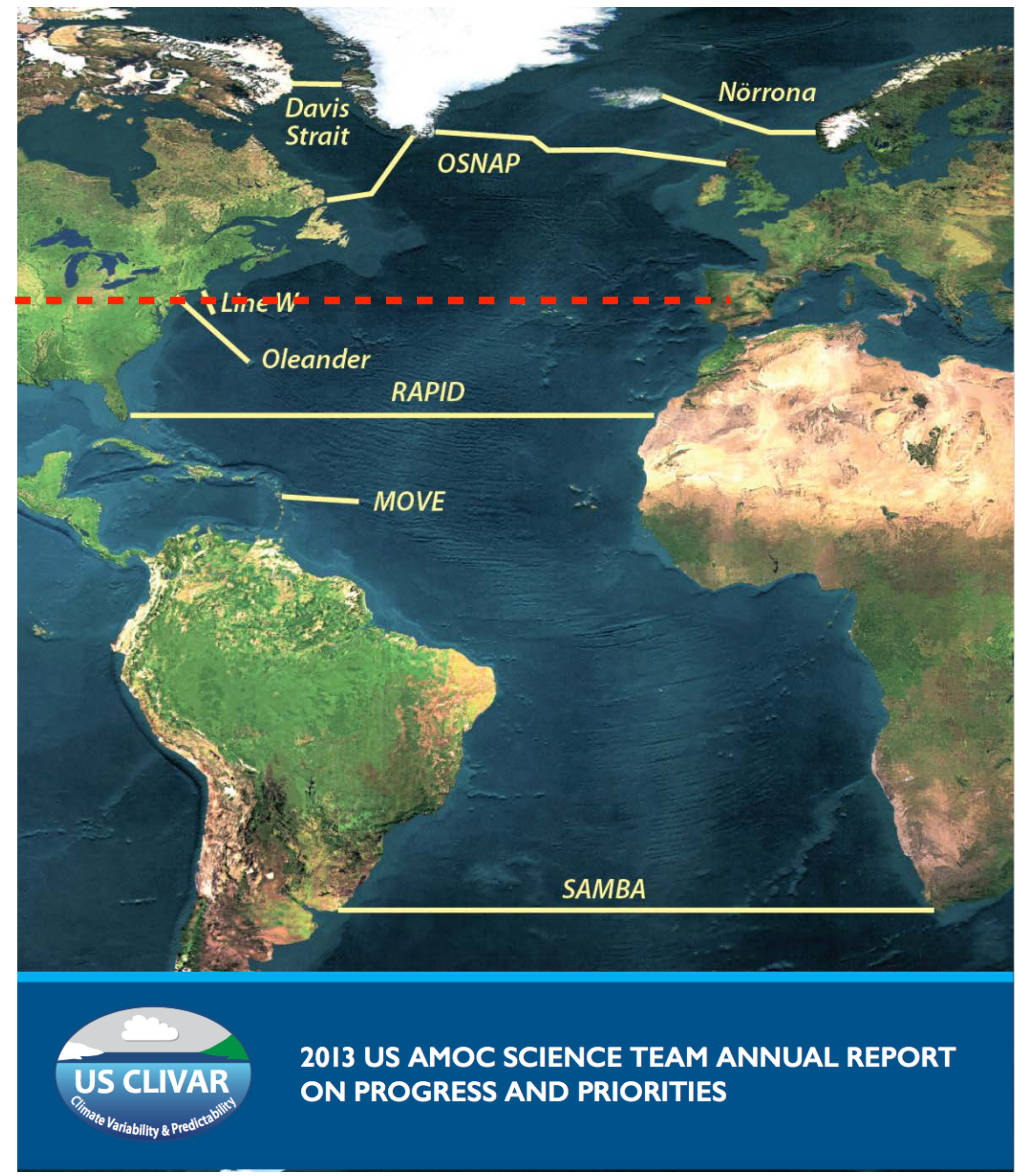
b) (b) Estimate of global ocean circulation patterns based on the box model inversion of *Ganachaud and Wunsch* [[6]]. The circulation is separated into three layers: shallow (red, <2 km), deep (blue, 2–4 km), and bottom (green, >4 km). Colored arrows across the sections (solid black lines) indicate the volume transport in Sverdrups. Circles represent the vertical transport out of the layer (open circle with dot for upwelling and open circle with cross for downwelling) [from *Marshall and Plumb*, [7]] (modified from *Alley et al.* [[8]]).

AMOC “trans-basin” measurements

Perez et al. 2015



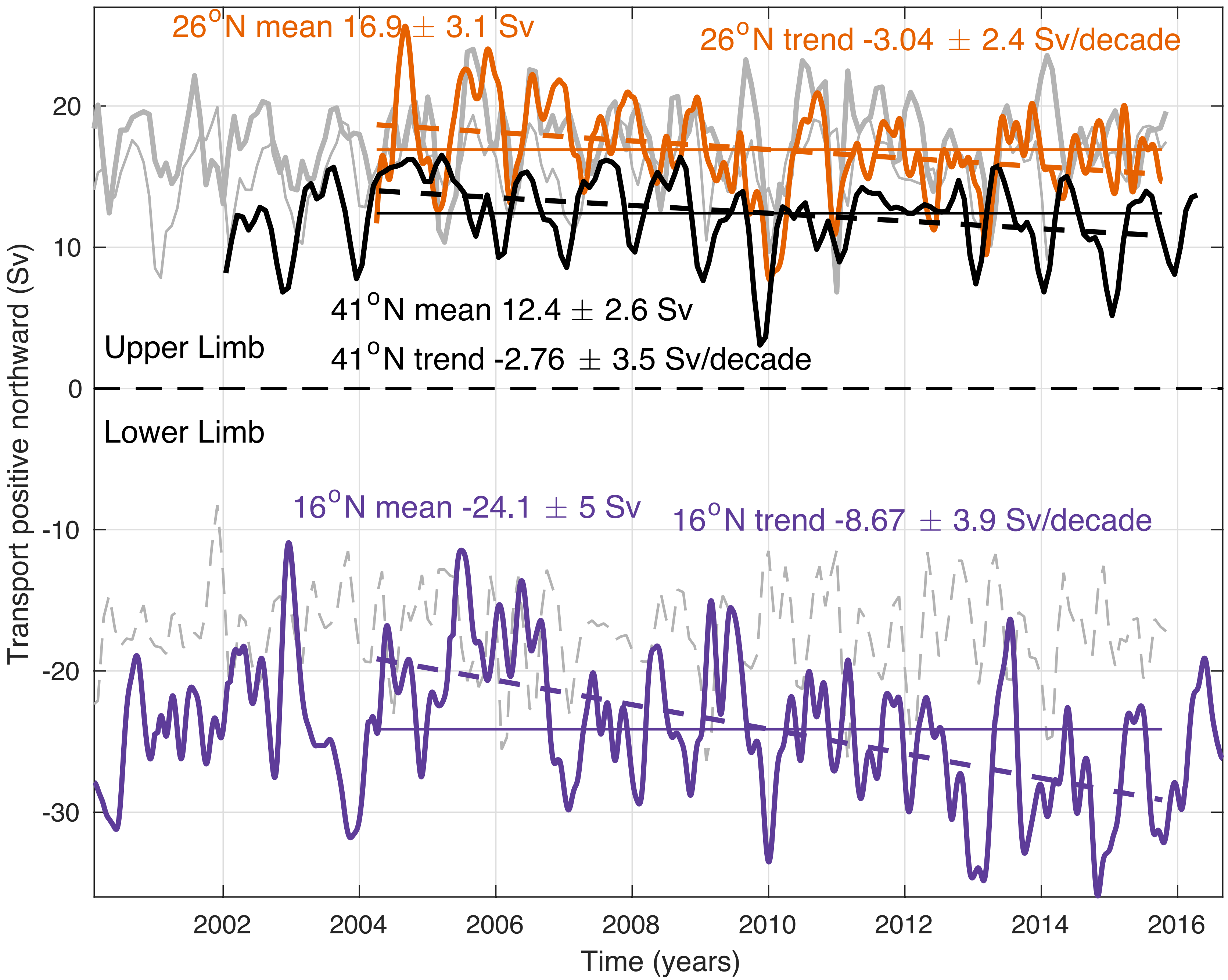
US AMOC report 2013



Yellow solid lines indicate locations of moored arrays, red dashed lines indicate repeat CTD transects, and black dotted lines indicate repeat XBT transects.

AMOC Processes

AMOC processes as recorded by time series: **TRENDS**



Latest trends:

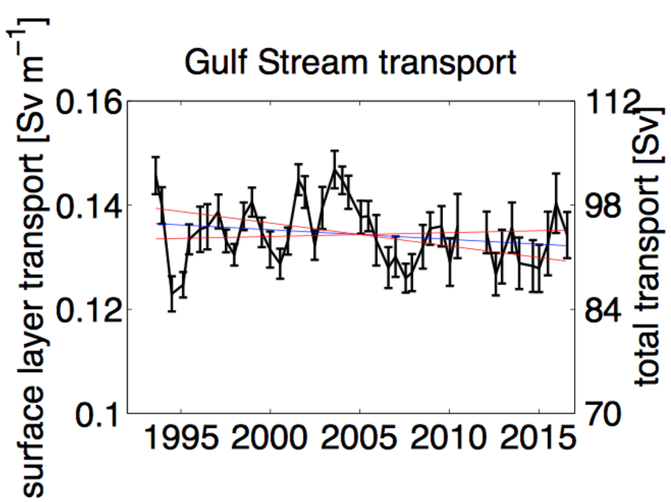
41N: -2.76 +/- 3.5 Sv/decade

26N: -3.04 +/- 2.4 Sv/decade

16N: -8.67 +/- 3.9 Sv/decade

Light gray lines show ECCO2-derived transports

BAMS State of the Climate 2015, 2016



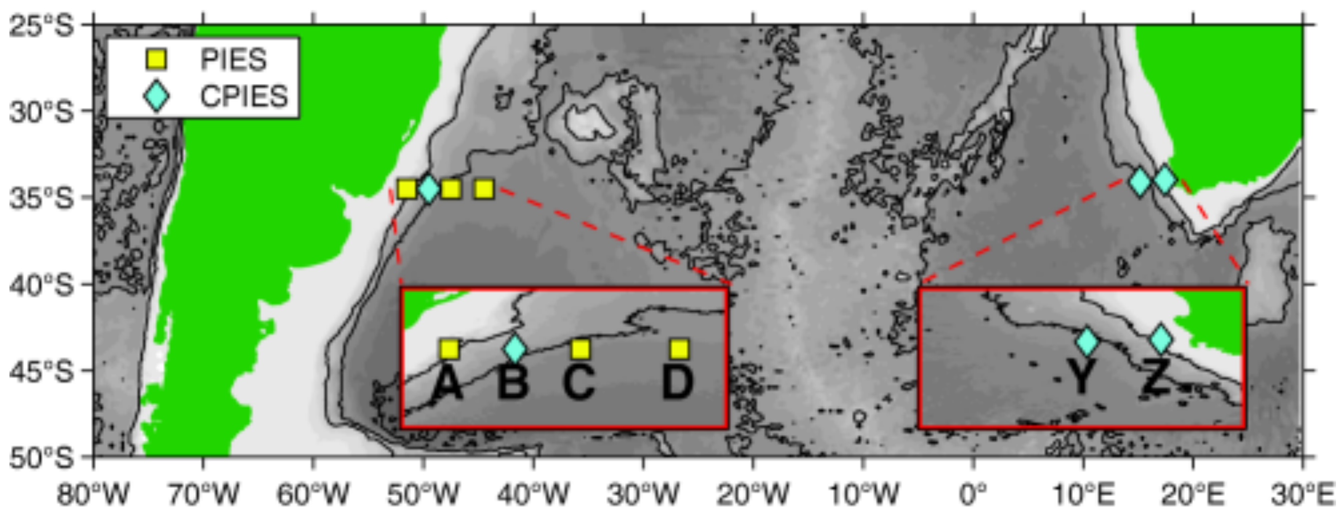
Updated from Rossby et al. 2014

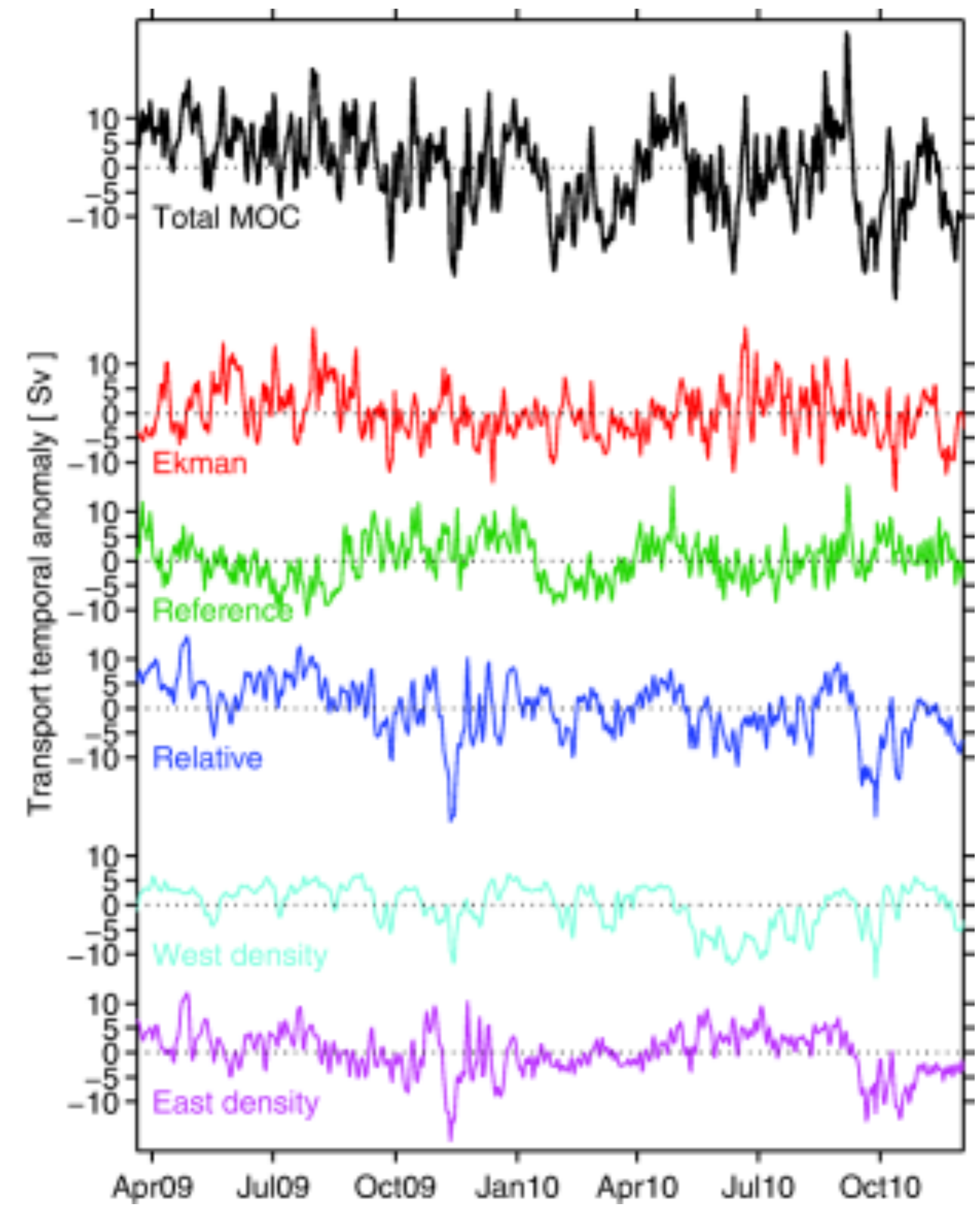
Donohue US AMOC 2017 poster: no trend in GS from Oleander measurements

AMOC Processes

AMOC processes as recorded by time series at 35 S

Meinen et al 2013

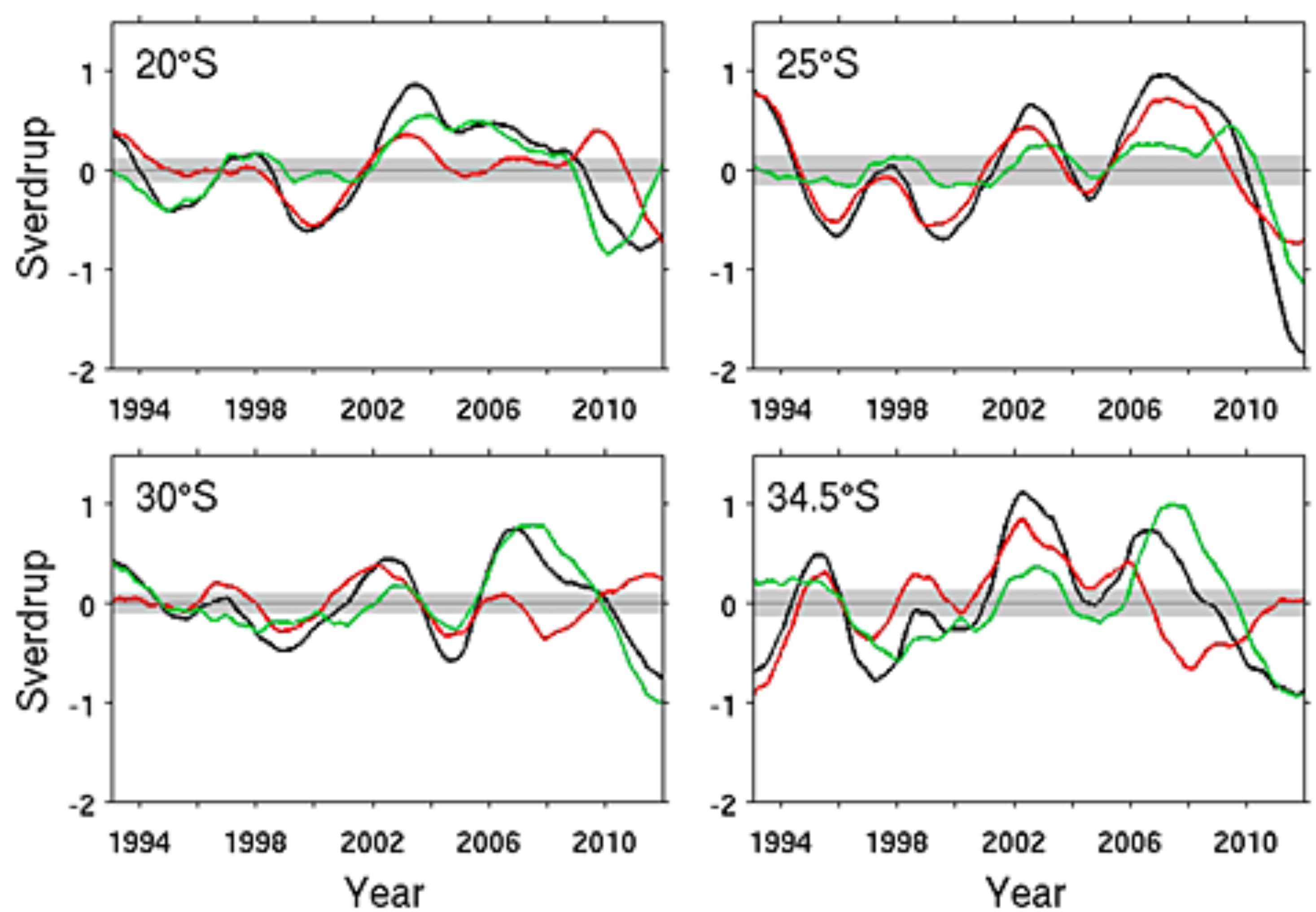




AMOC Processes

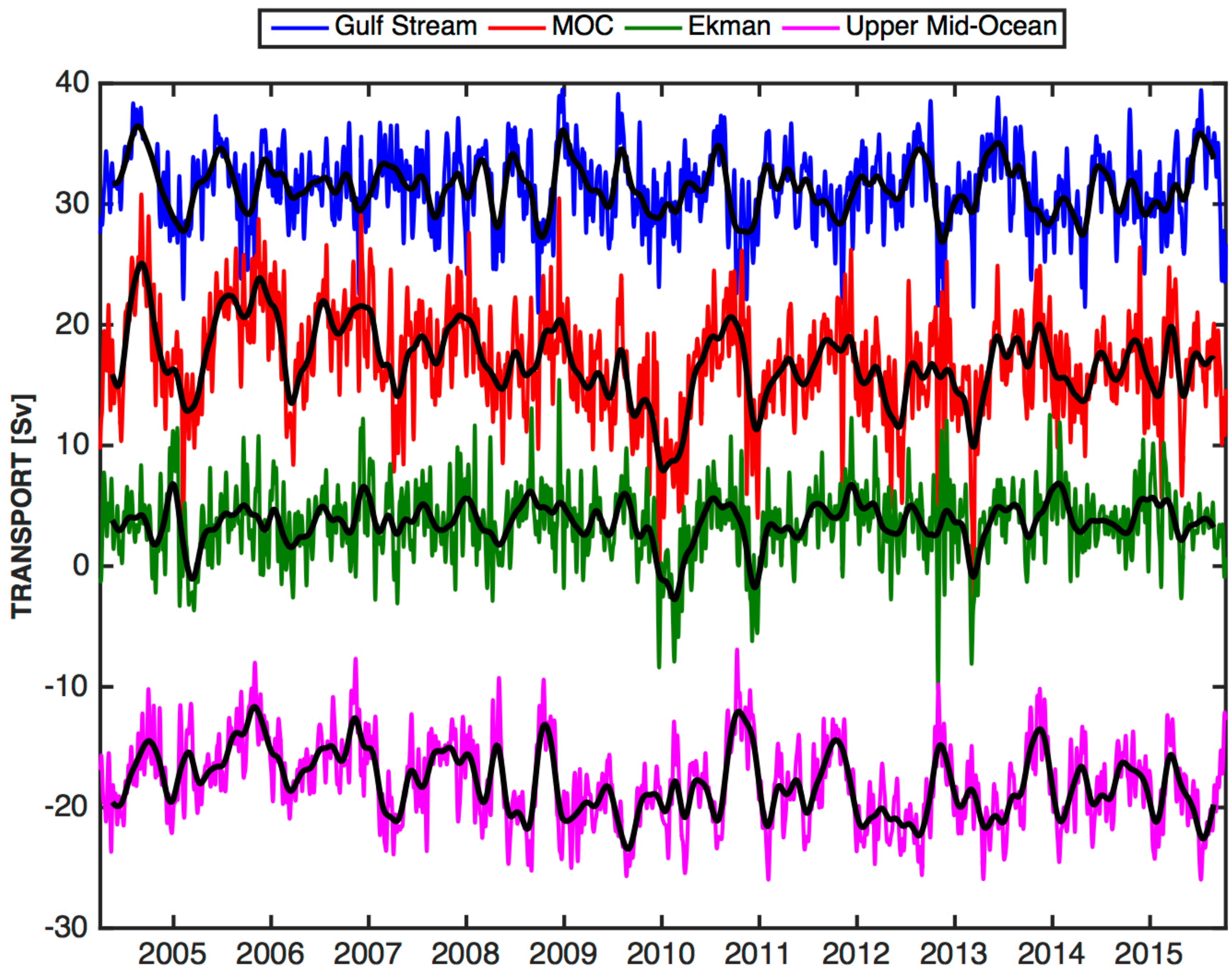
Components

Synthetic XBT/Altimetry MOC estimates in the South Atlantic
Interannual variations of the MOC (black) and contributions from the geostrophic (red) and Ekman (green) components



AMOC Processes

26N Components

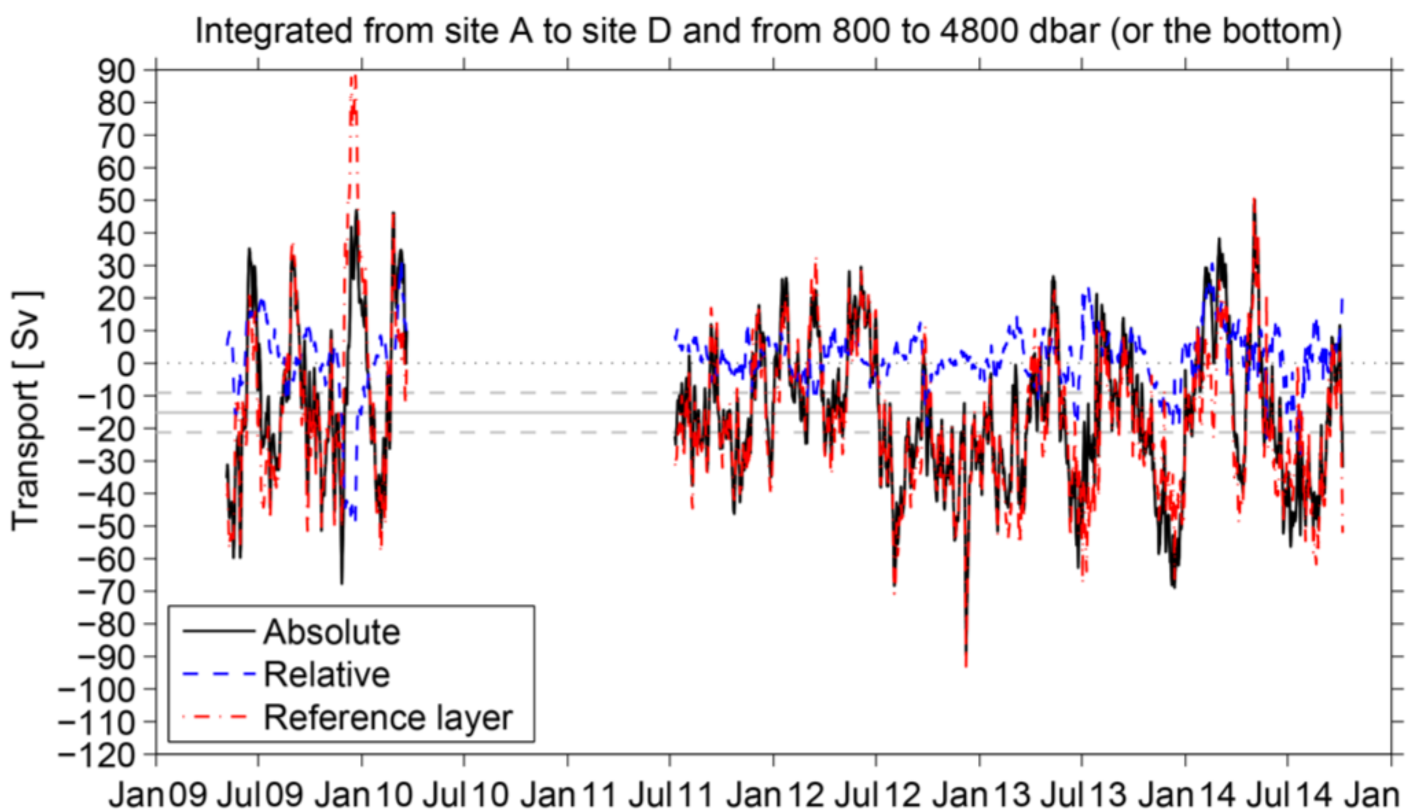


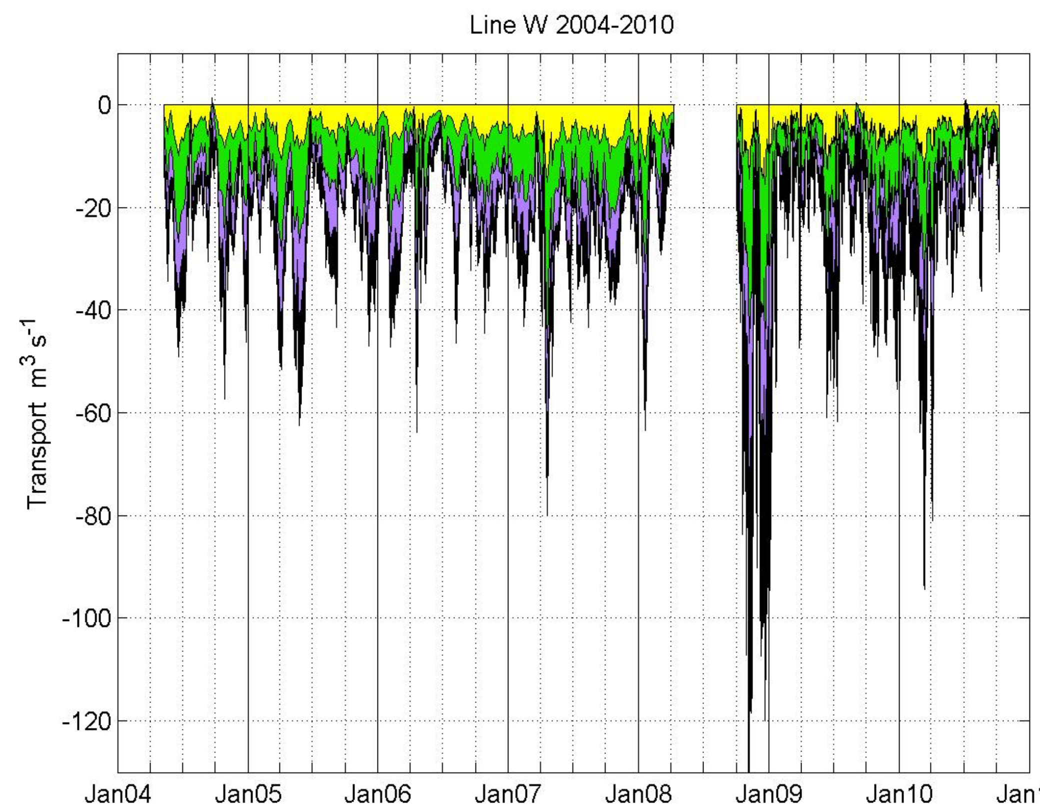
AMOC Processes

Components: Deep Western Boundary Currents

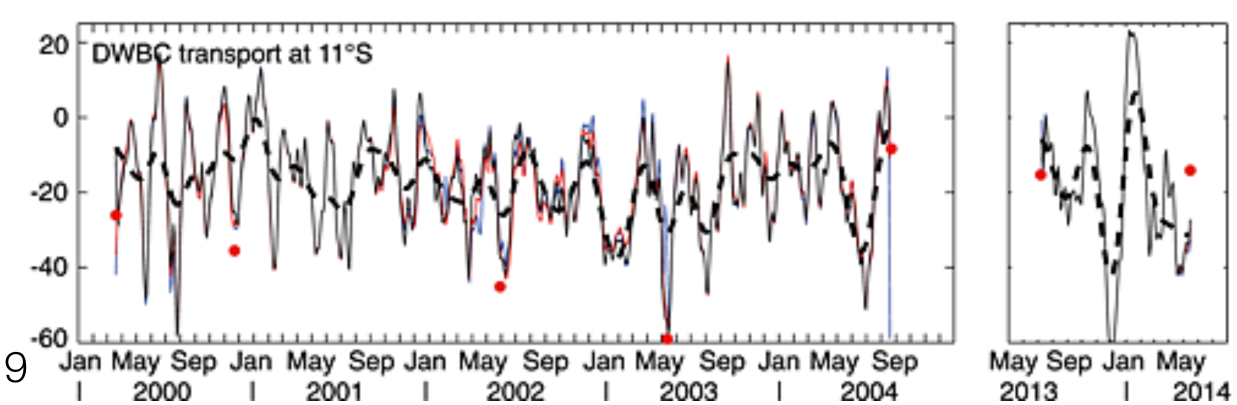
No clear relationship to AMOC time series; missing dynamical framework with AMOC

At 26 N Meinen et al. 2017 At 39 N Line W Toole et al. 2011





Hummels et al. 2015 : WBC at 11S



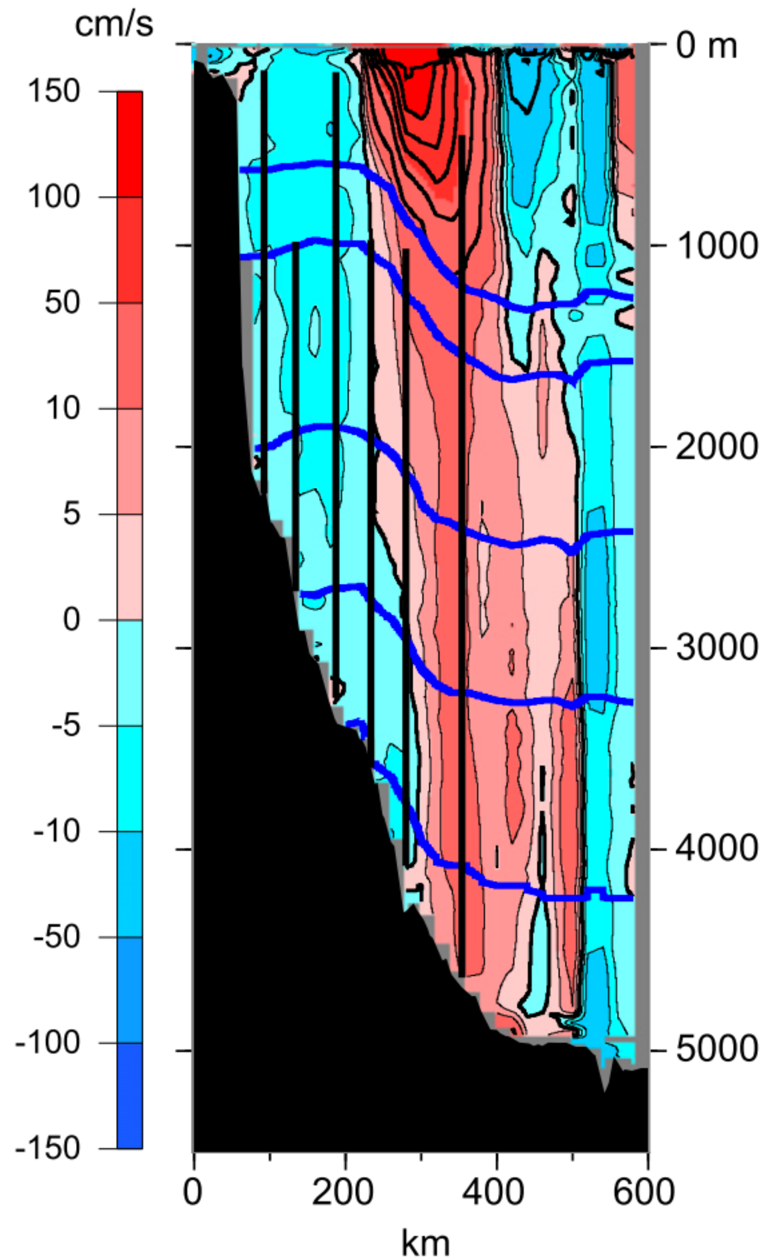
AMOC Processes

Components: Deep Western Boundary Currents

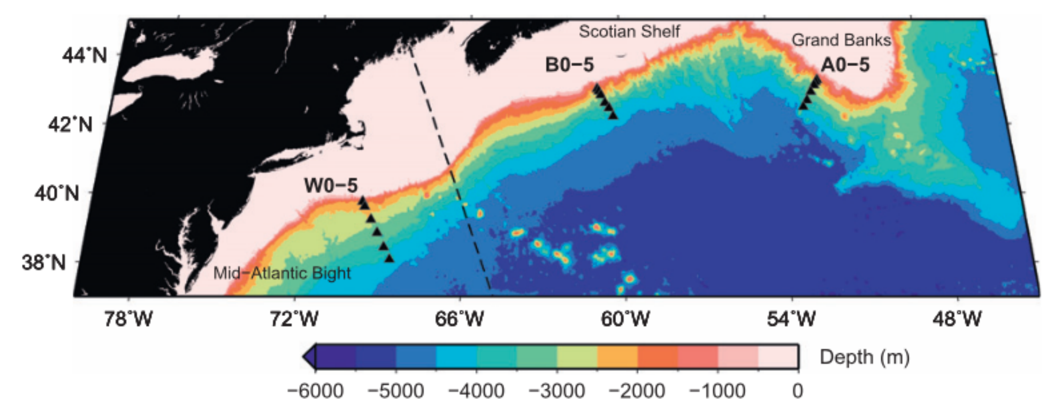
39 N

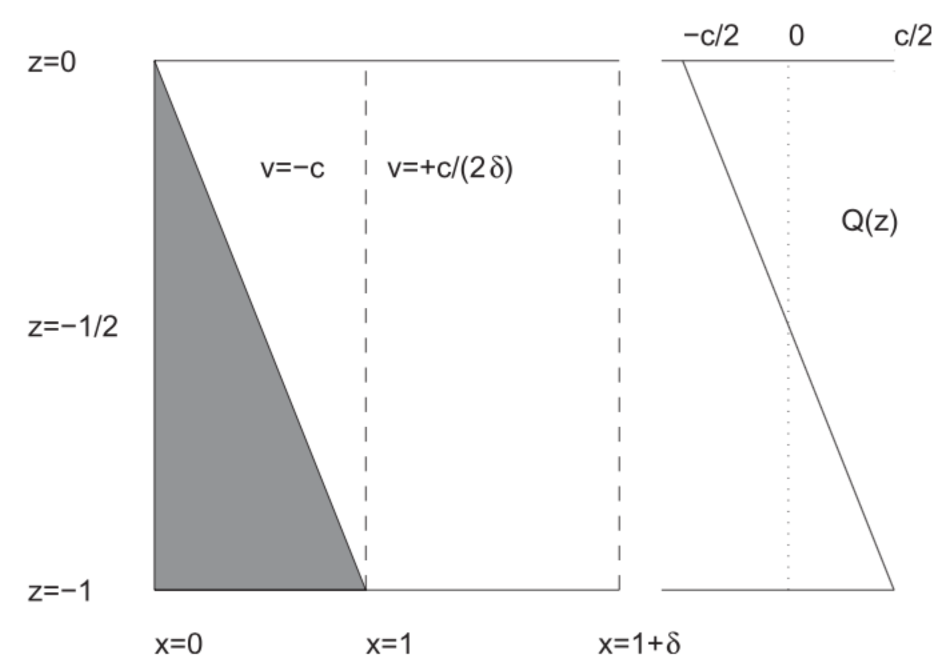
WBC flowing on boundary influences bottom pressure hence overturning transports

Toole et al. 2011



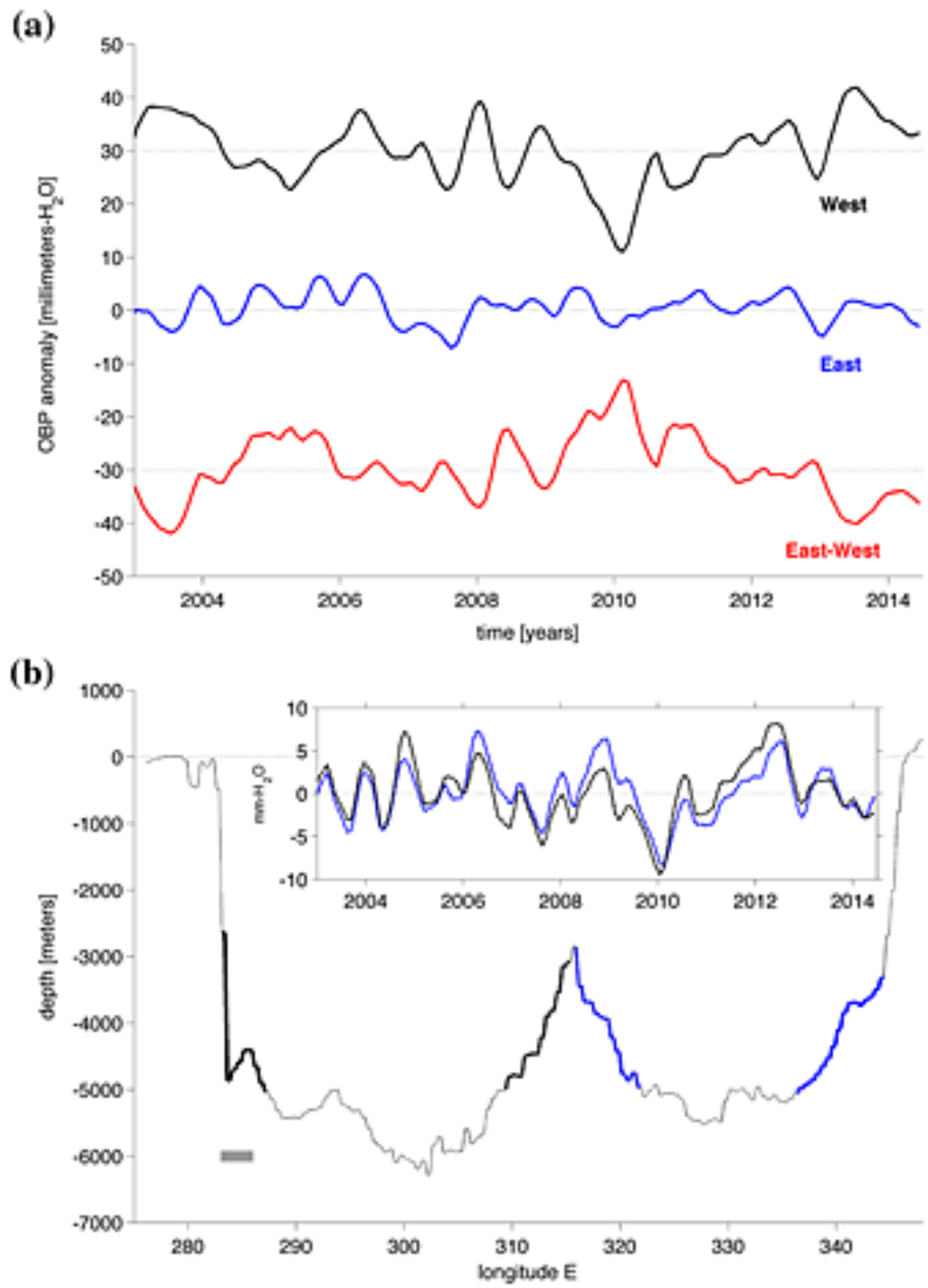
Elipot et al. 2013





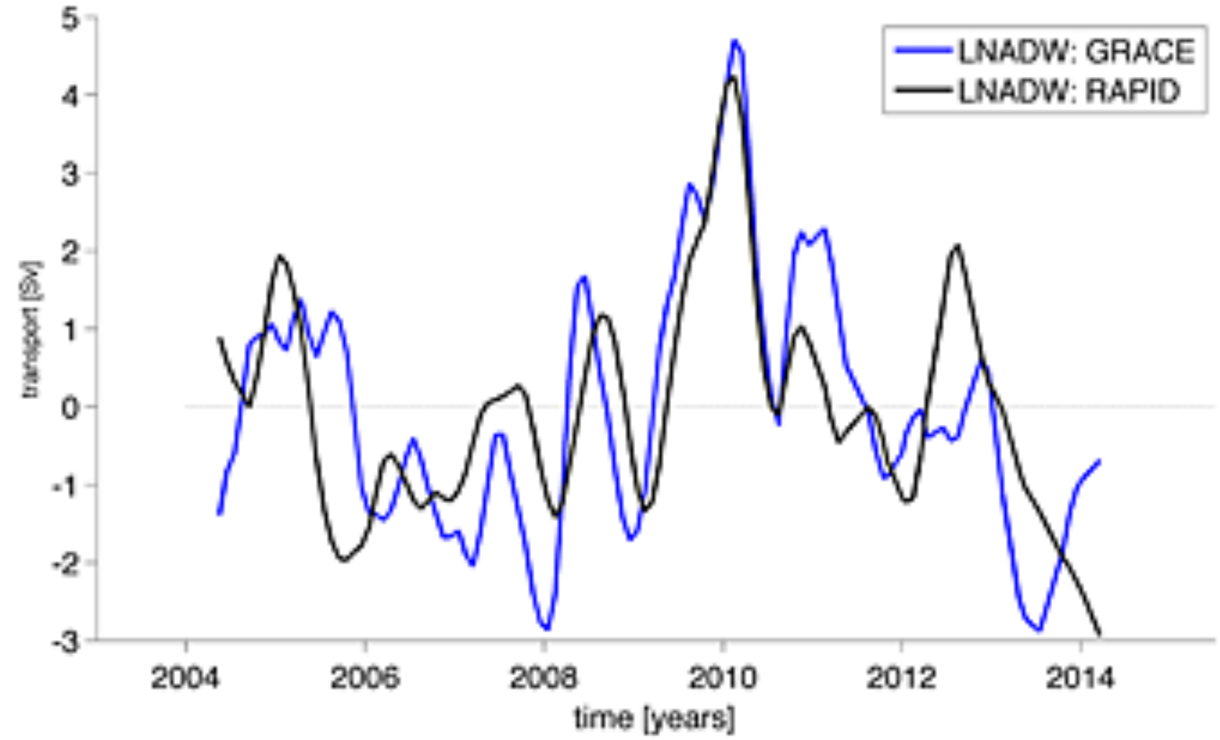
AMOC and Ocean Bottom Pressure (OBP)

26 N OBP from GRACE



MAR does not matter much

3000-5000 m transport from OBP compared to RAPID

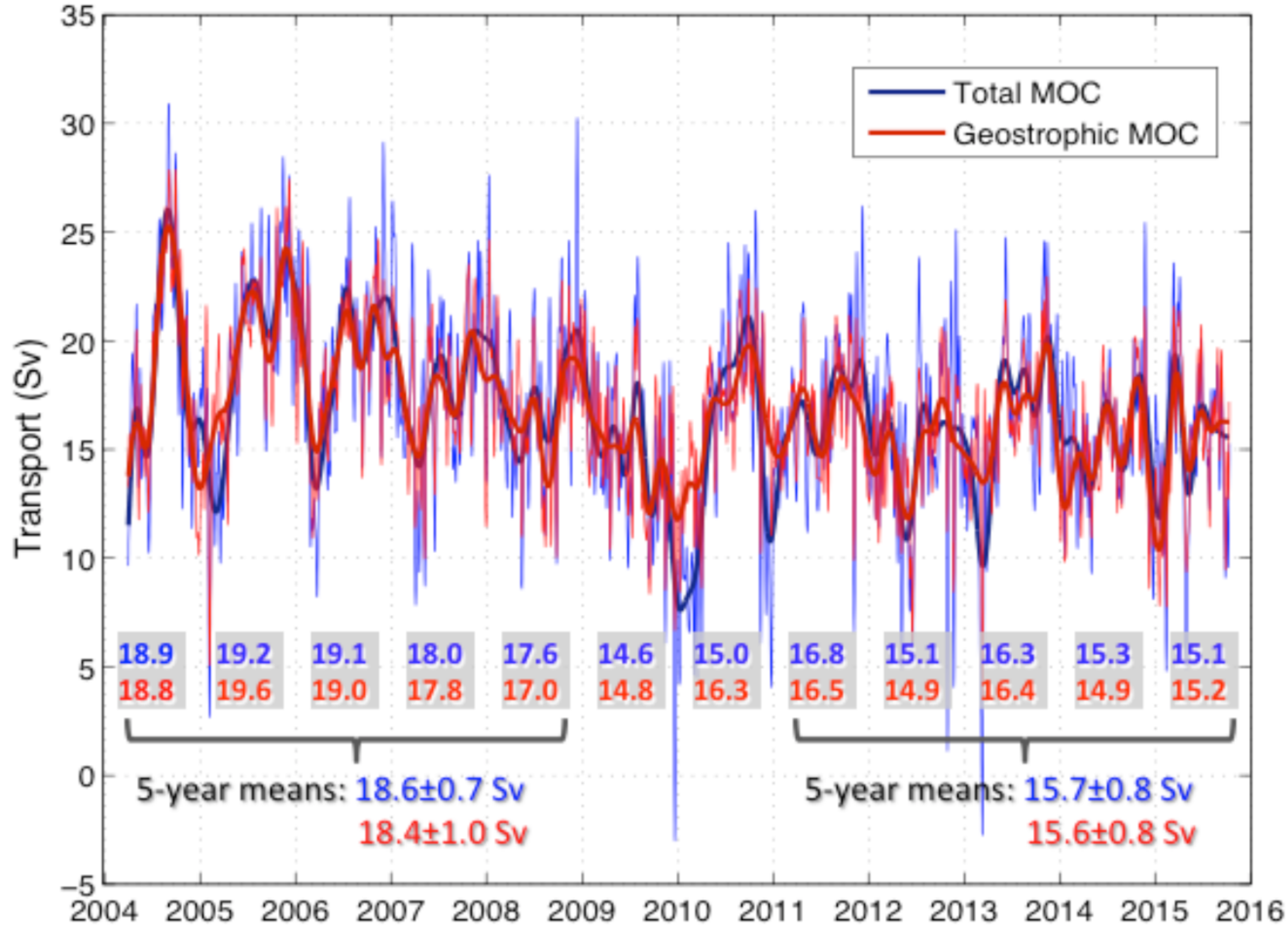


OBP is boundary pressure so its east-west difference captures transport

Landerer et al. 2015

AMOC Processes; Components: geostrophic

26 N : geostrophic transport dominates the means

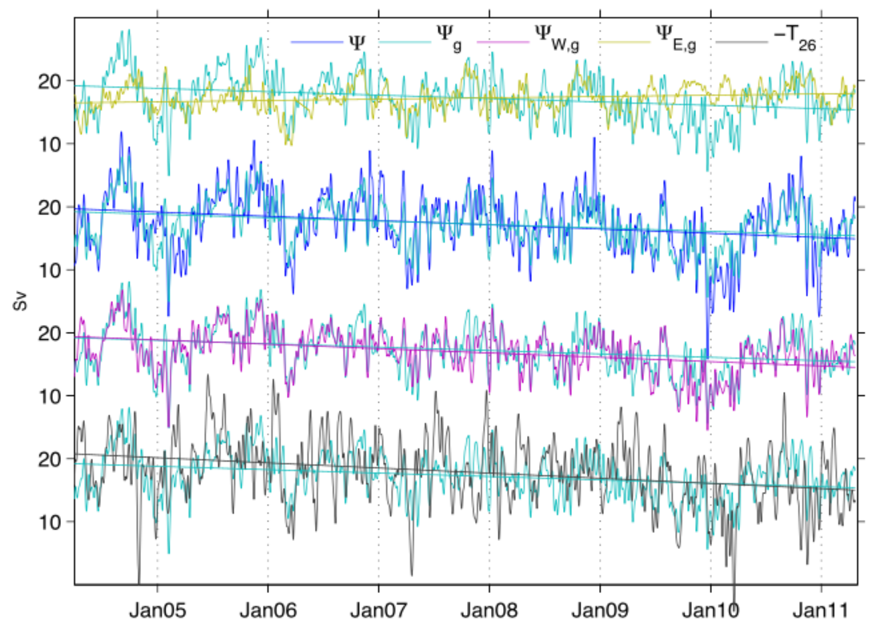


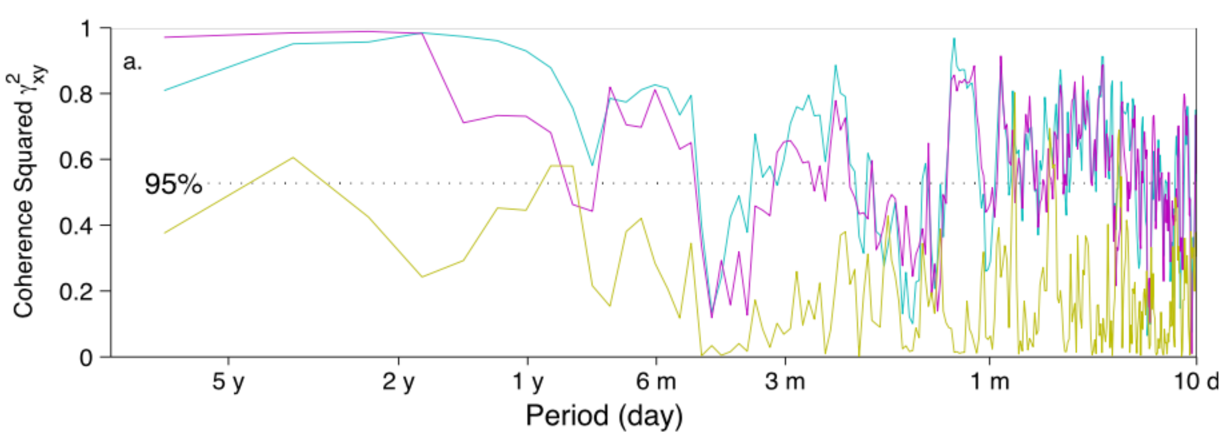
Source: US AMOC 2016 report ; Johns et al.

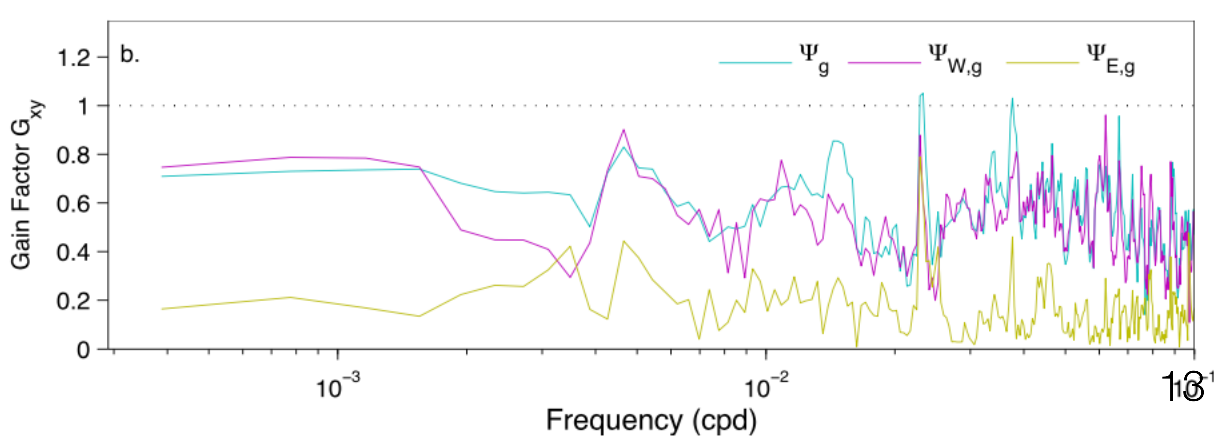
AMOC Processes; Components: geostrophic

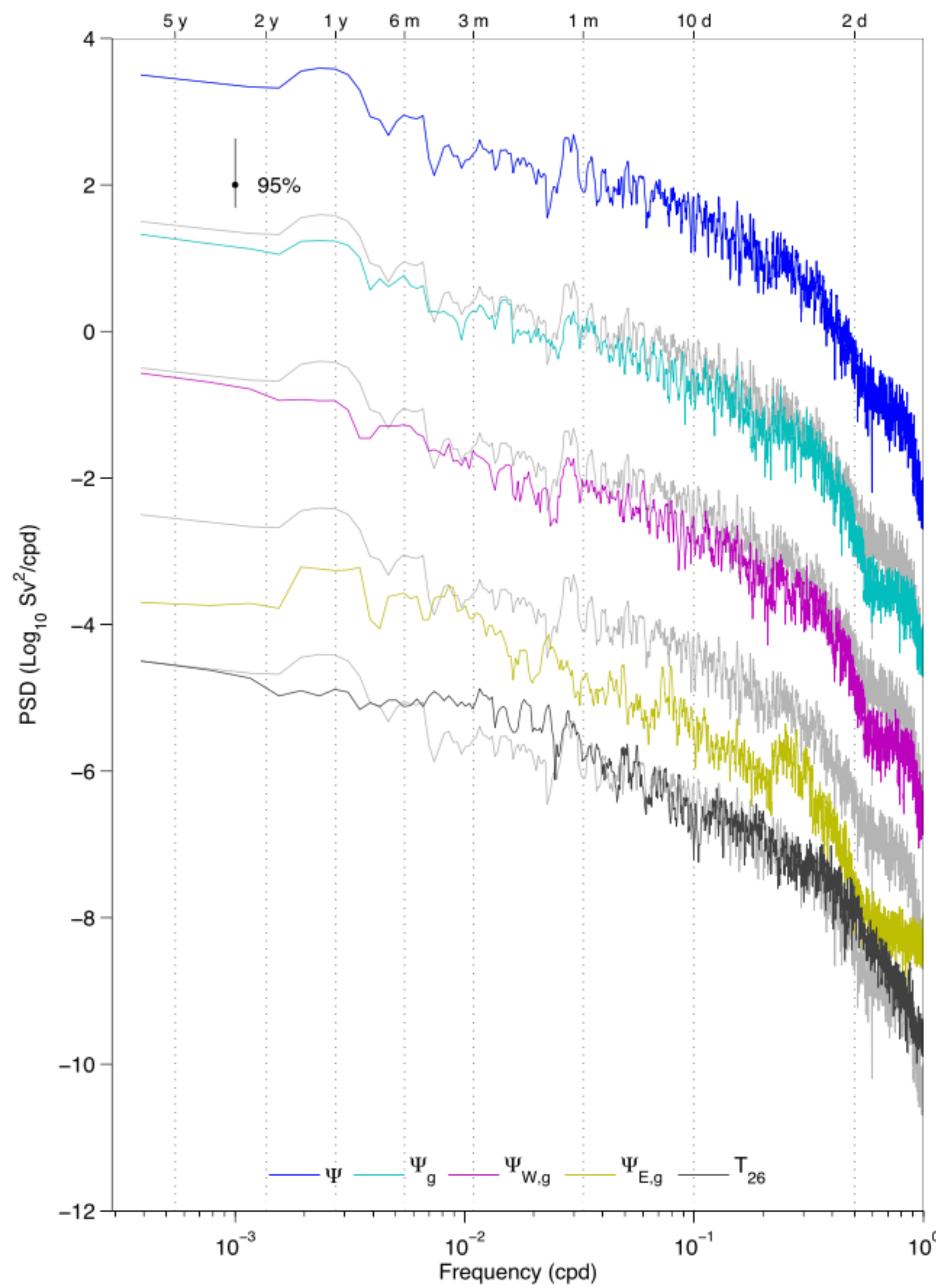
26 N: geostrophic transport dominates also the variance

Elipot et al. 2014









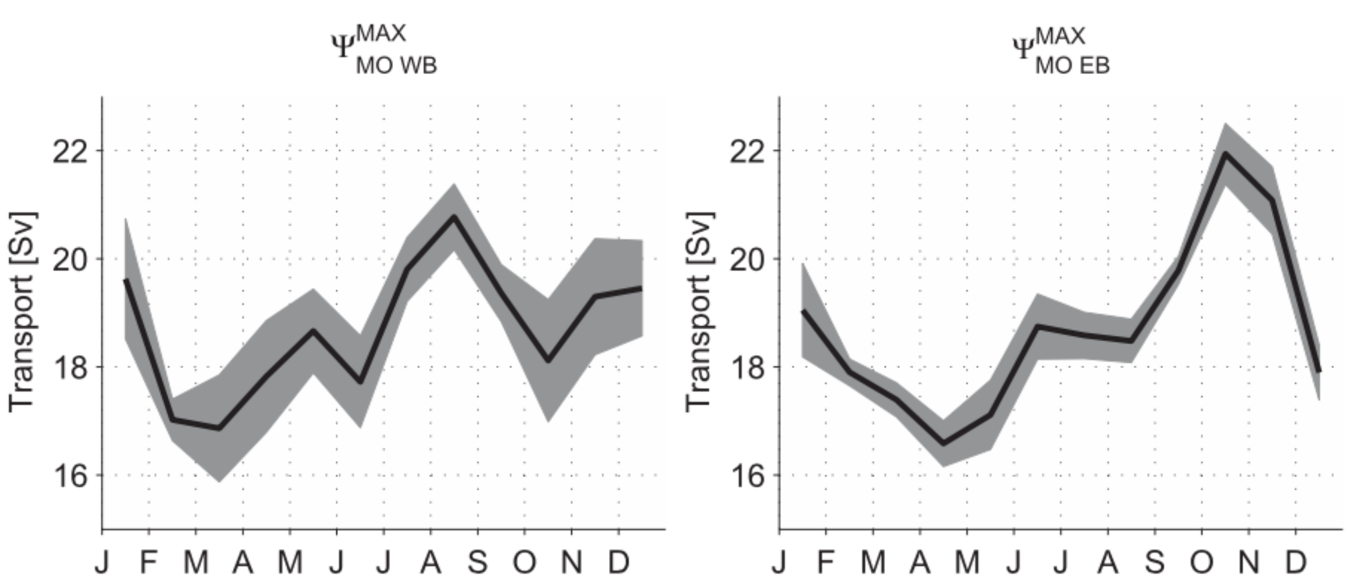
Seasonal processes

are boundary processes in observations

Kanzow et al 2009

Zhao and Johns 2014a

26 N



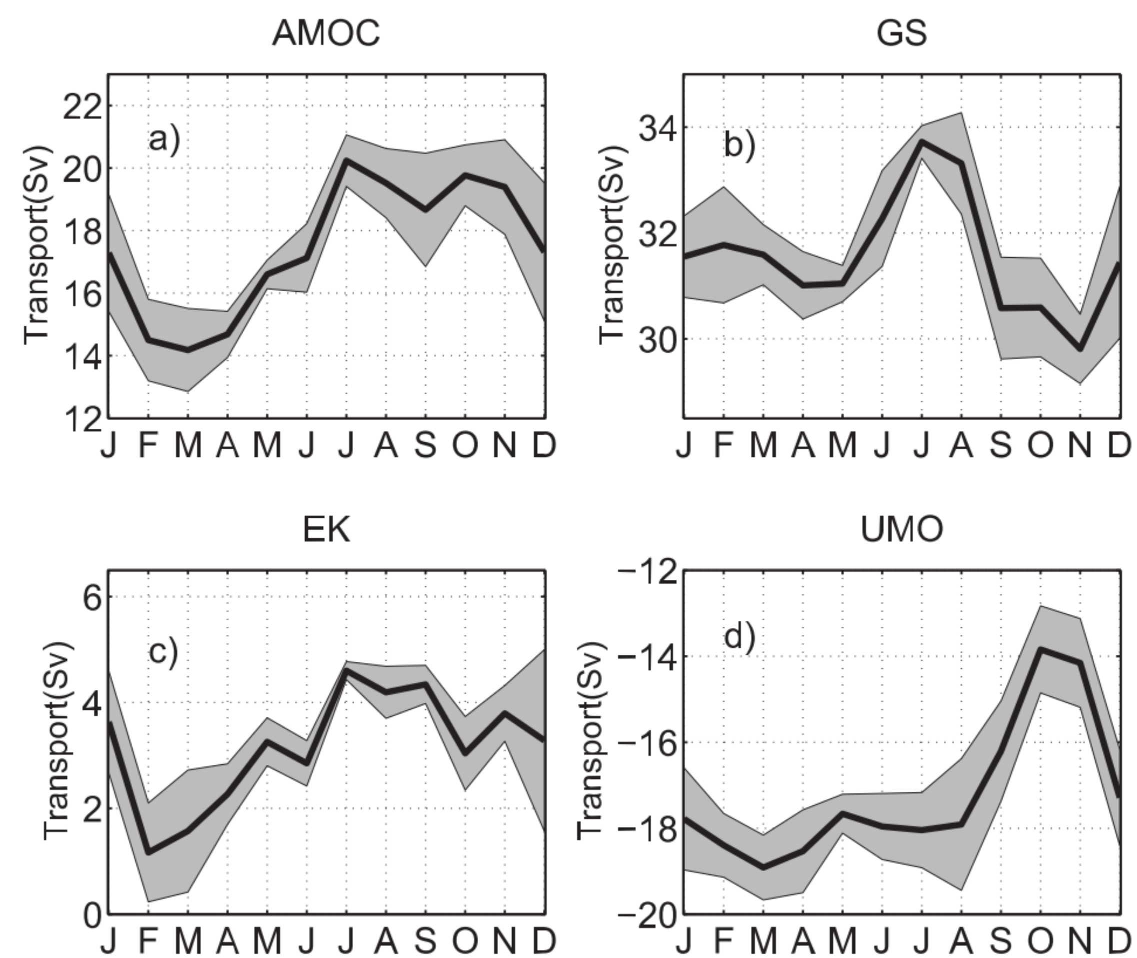


FIG. 3. Seasonal cycle (black solid lines) of (a) AMOC, (b) GS, (c) EK, and (d) UMO, as obtained from monthly averages of the 26.5°N time series between April 2004 and April 2011. The gray envelopes represent the std error of each month.

Seasonal processes

are latitude-dependent

Elipot et al. 2017

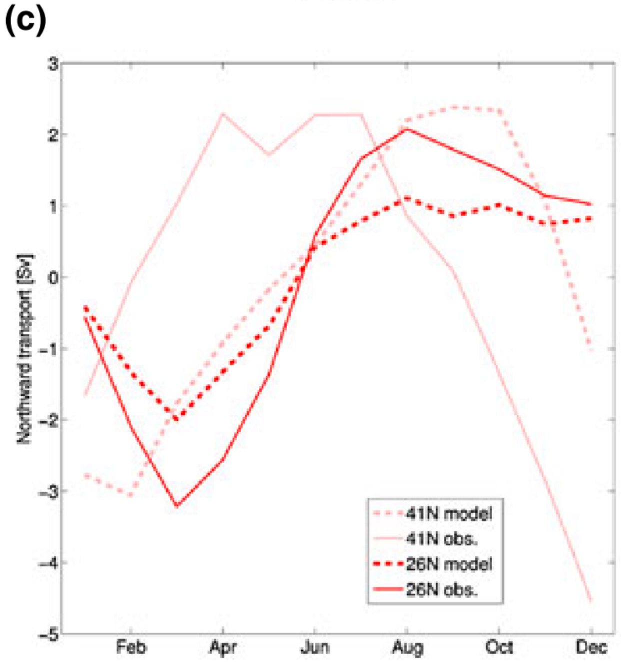
Mielke et al. 2013

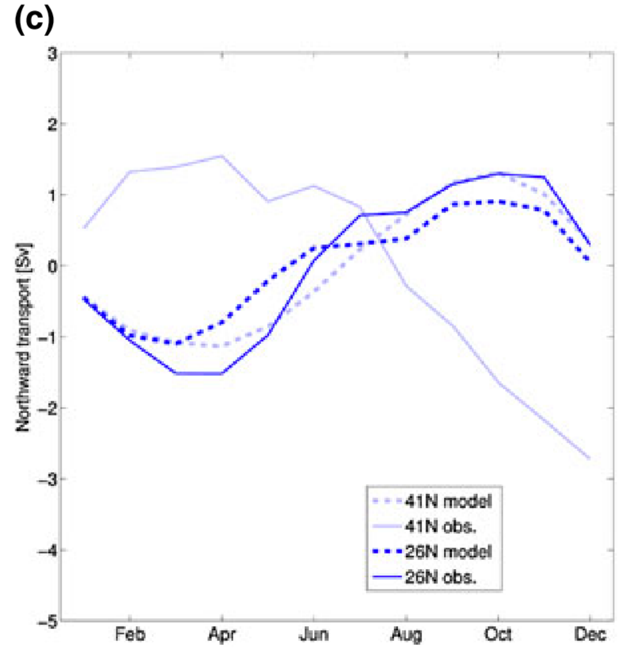
41N, 39N, 26N & 16N

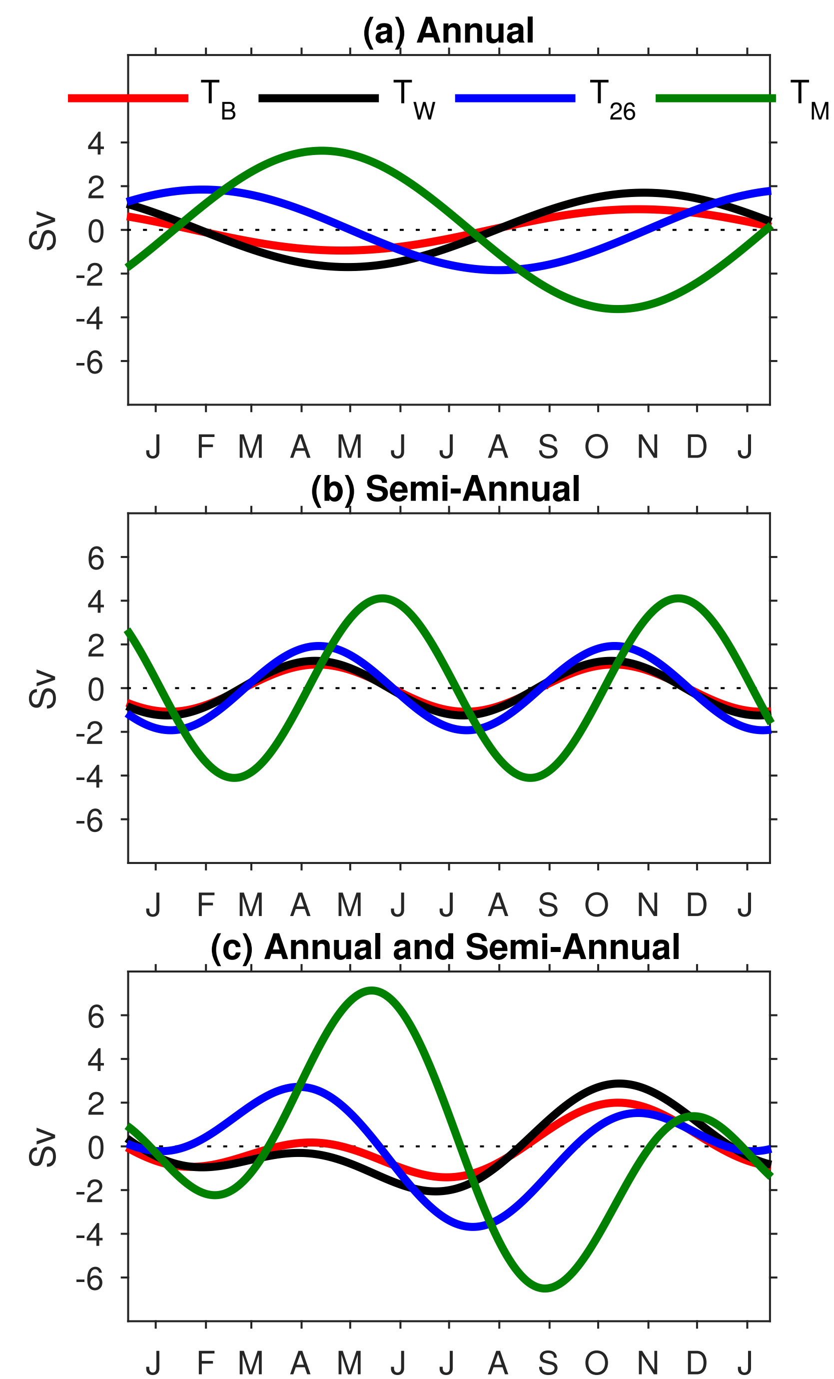
26 N & 41 N

MOC

MOC-EK





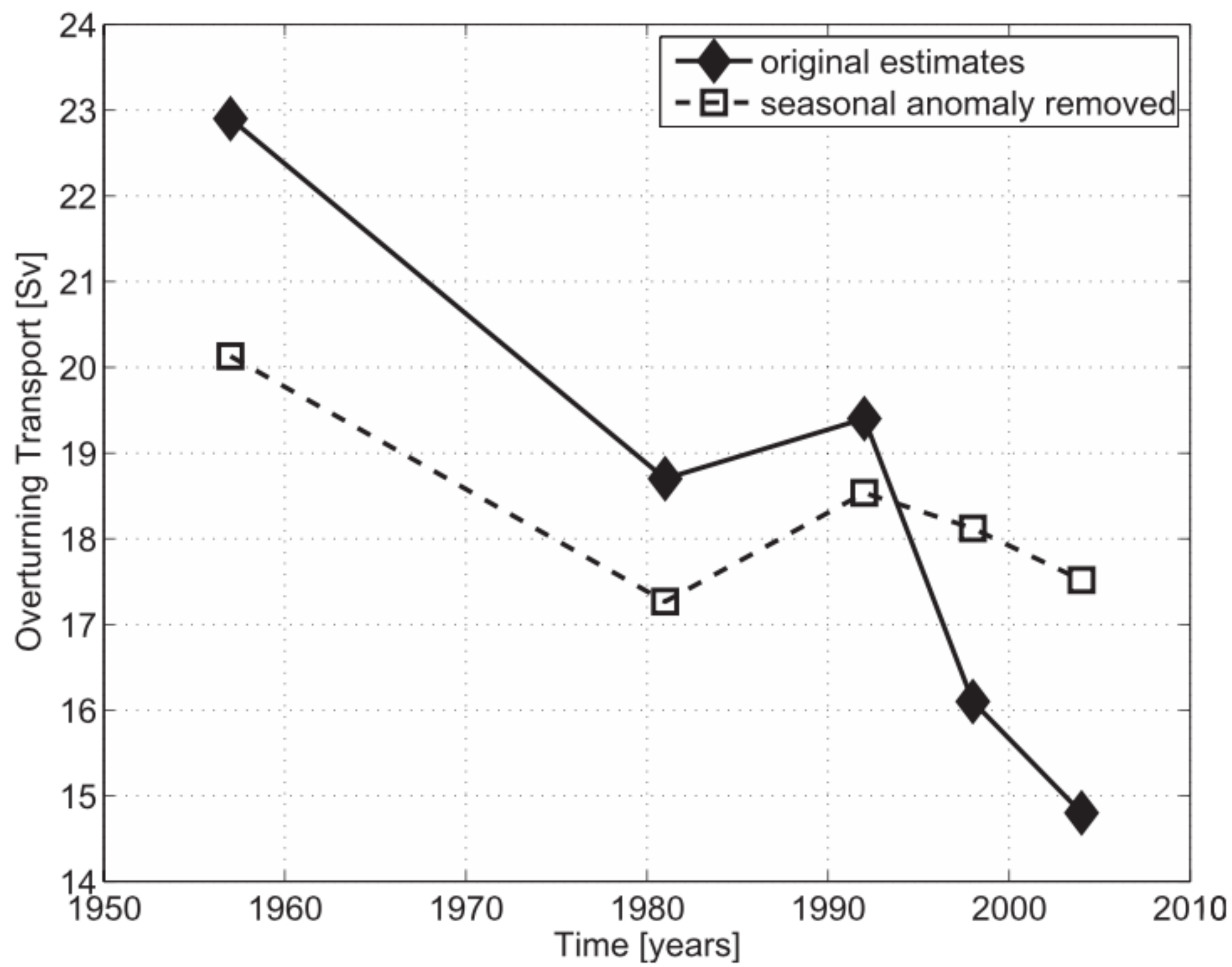


Geostrophic west contribution to MOC →

Seasonal processes

26 N: seasonal oscillations biased ship-based hydrographic estimates

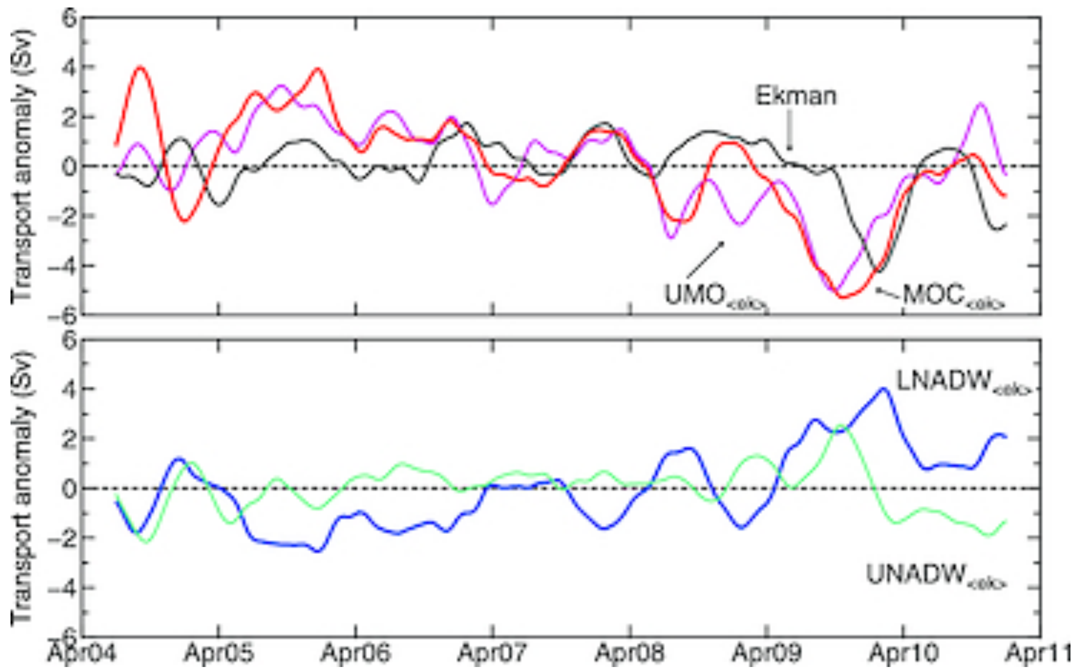
Kanzow et al. 2010



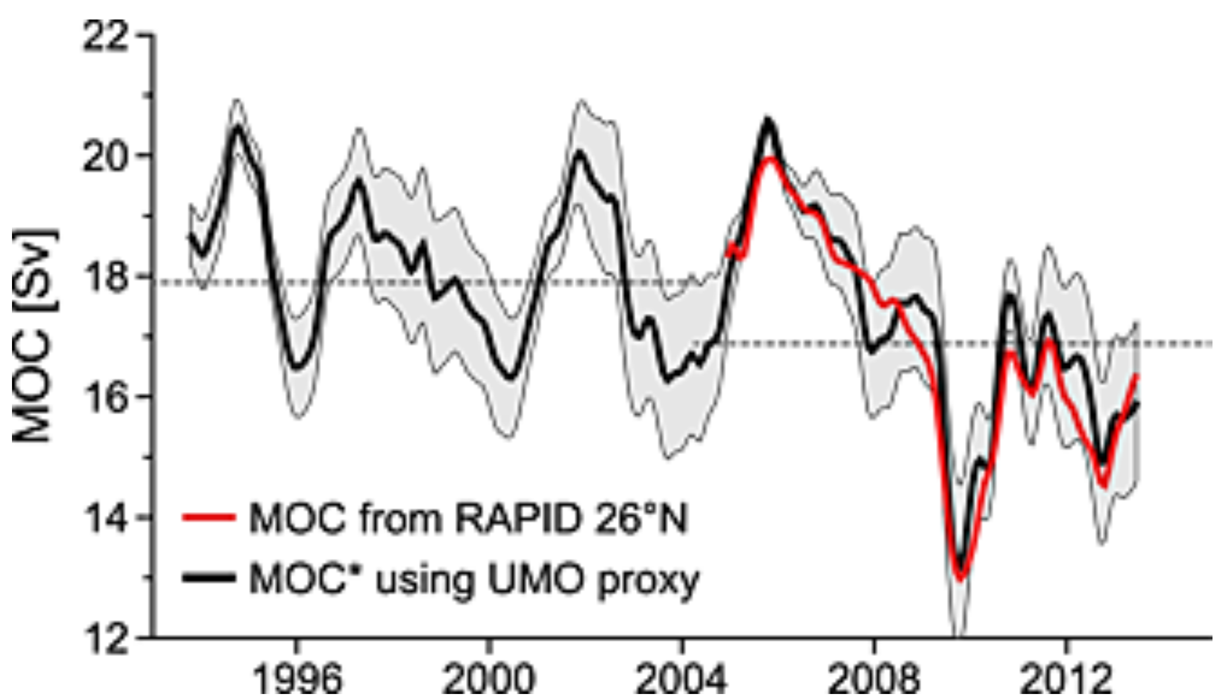
Interannual processes

are Ekman + geostrophic west (26 N)

McCarthy et al. 2015



Frajka-Williams 2015



Zhao and Johns 2014b

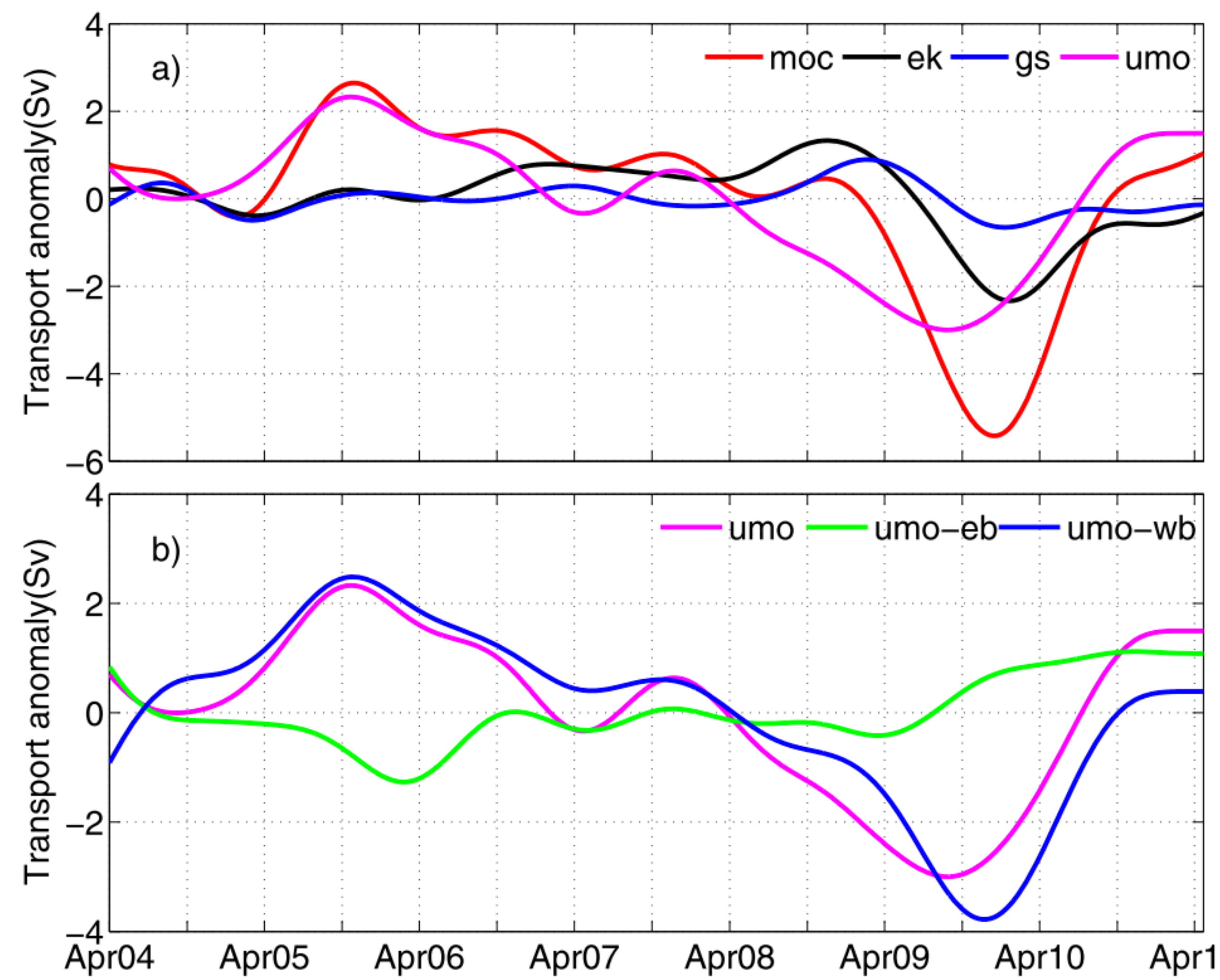
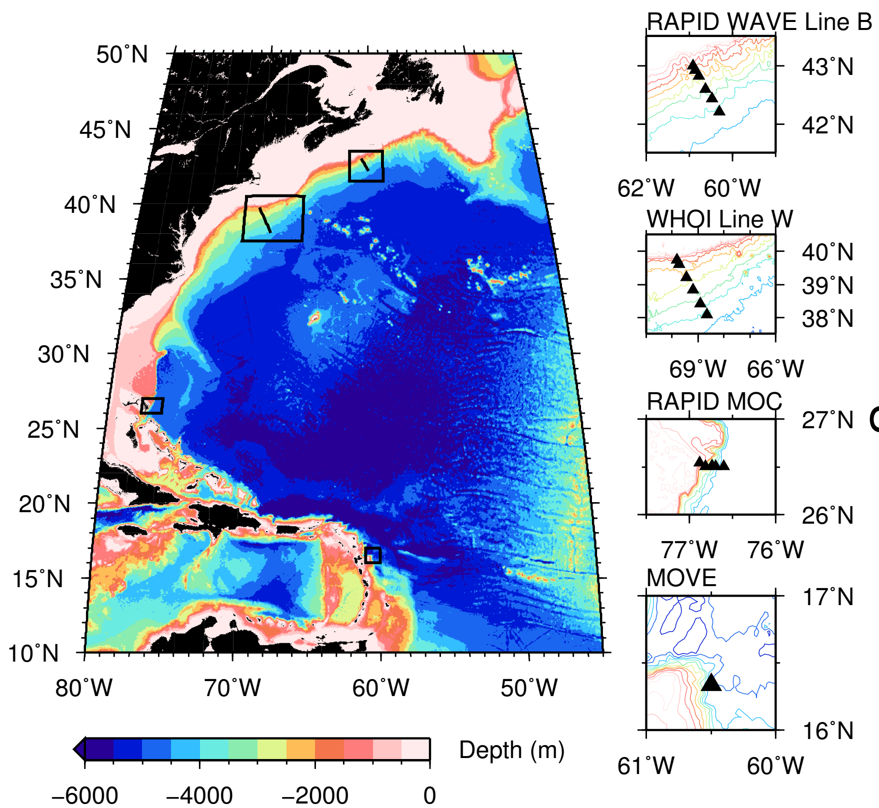


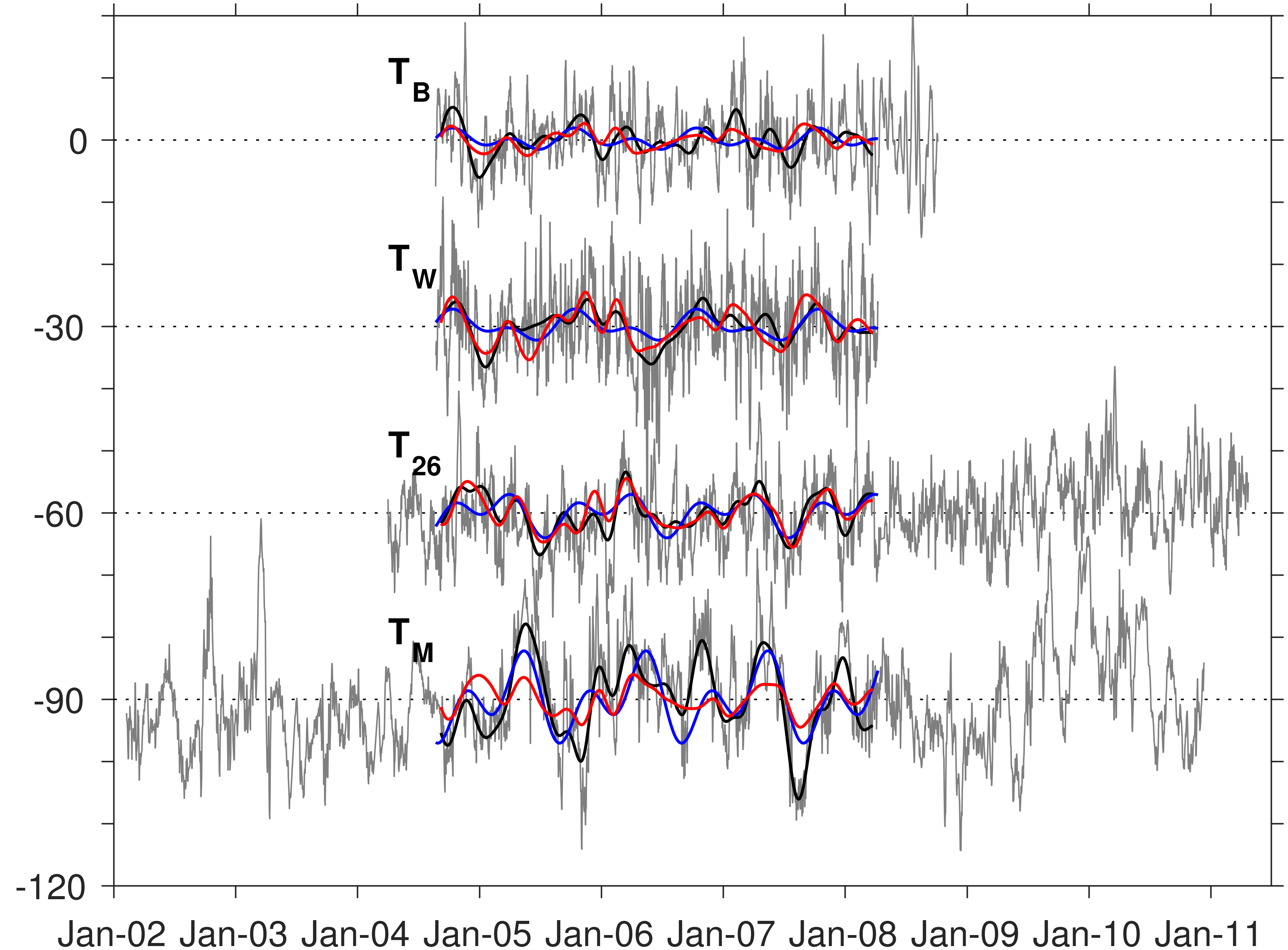
Figure 2. The 18 month Butterworth low-pass filtered time series of T_{AMOC} (red), T_{GS} (blue), T_{EK} (black) and T_{UMO} (magenta), $T_{UMO\text{-}eb}$ (green), and $T_{UMO\text{-}wb}$ (blue) for the period between April 2004 and April 2011. $T_{UMO\text{-}eb}$ and $T_{UMO\text{-}wb}$ are calculated by fixing the density profile at the western boundary and the eastern boundary, respectively, to their mean values. The temporal mean values are removed to obtain the interannual anomaly. Unit: Sv.

Coherence by wind forcing

41 N, 39 N, 26 N and 16 N

Elipot et al. 2017





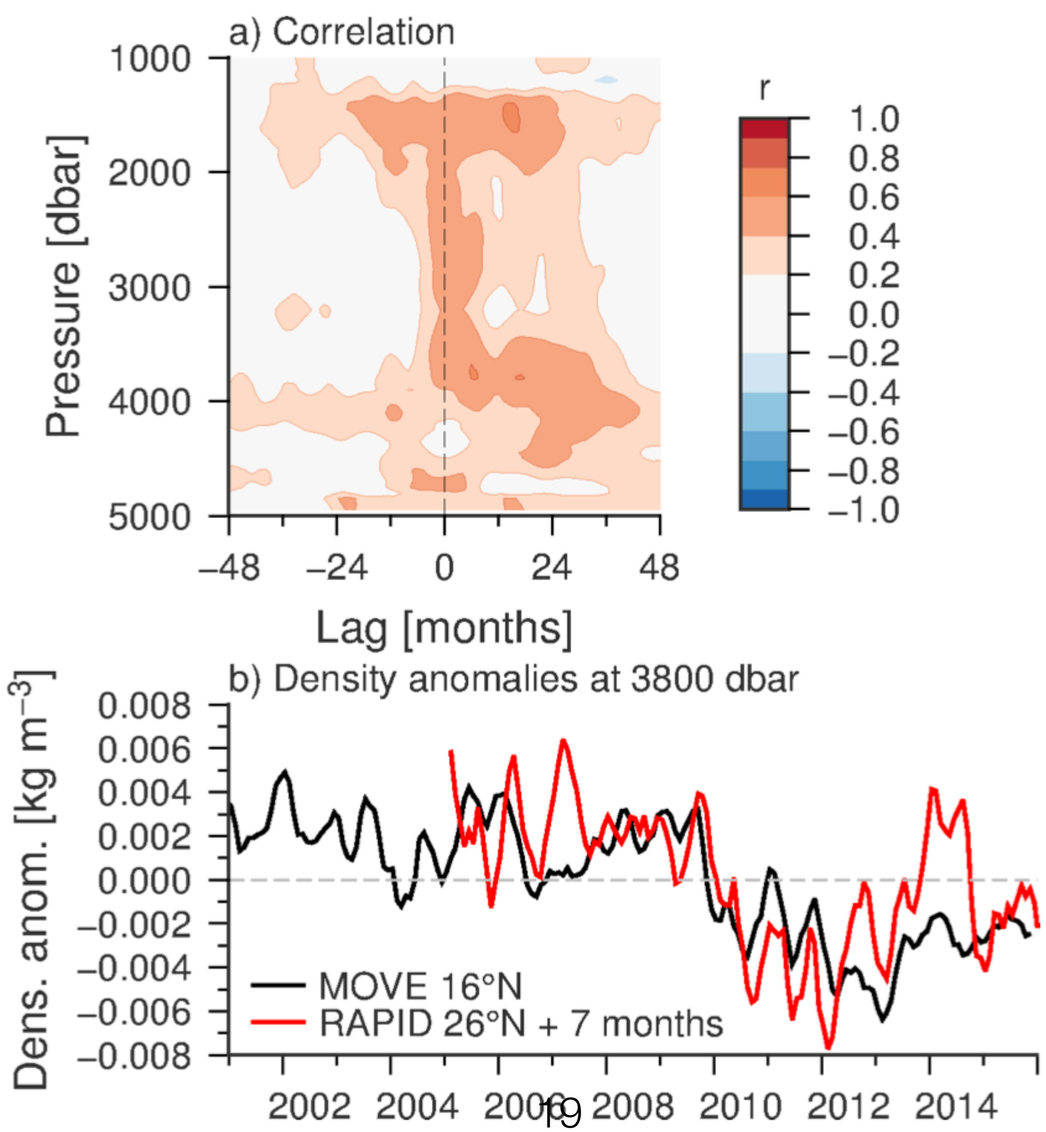
Four 3.6-yr time series of western boundary contribution to overturning transport between 1000 m and 4000 m referenced to 1000 m: more than 50% of 3-month lowpass variance explained by wind forcing (seasonal+NAO)

12-h time series, 3-month low-pass-filtered, real part of the 3-month low-pass-filtered projections of AEOF1, fits to annual and semiannual cycles.

Coherence of AMOC

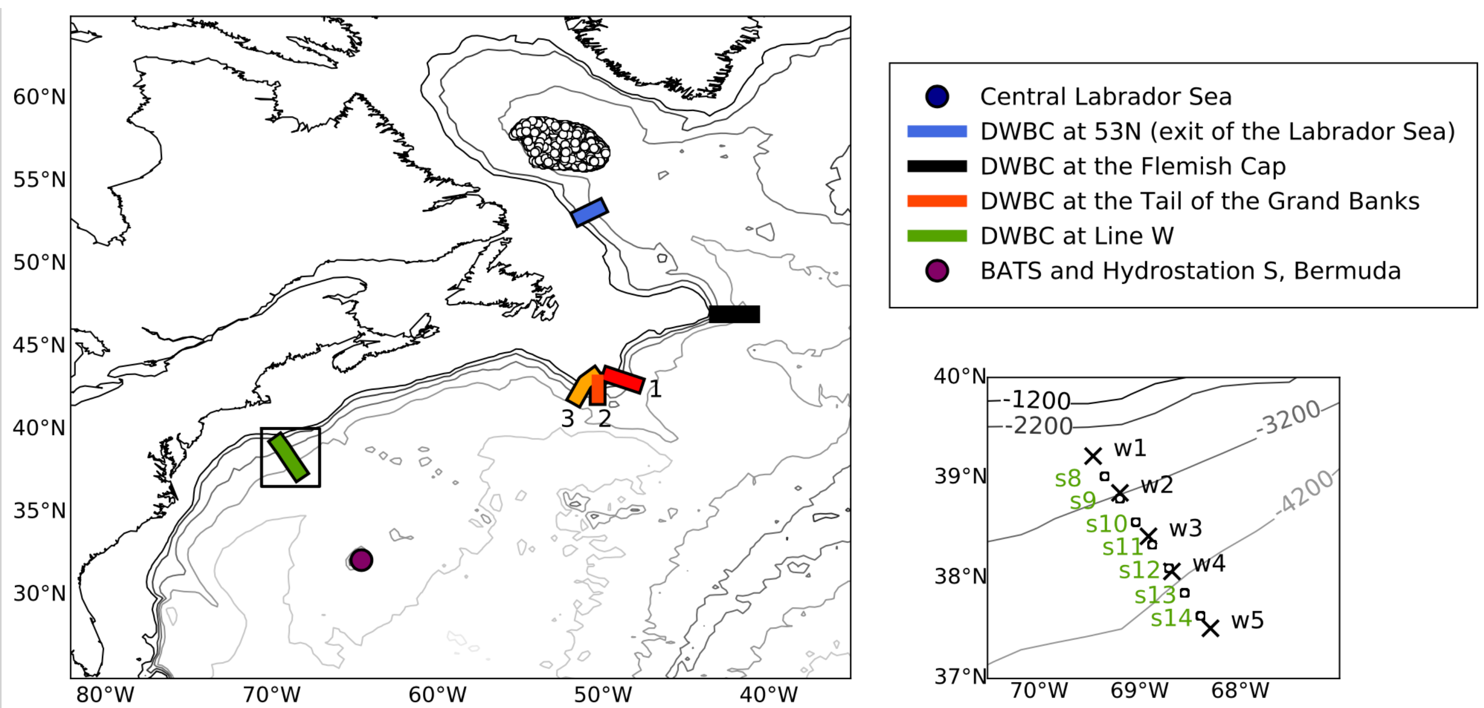
Frajka-Williams et al. 2016 submitted

density correlations between 16N (MOVE) and 26N (RAPID). Changes observed at the western boundary show consistent tendencies (towards freshening, lightening and an increase in deep shear of the southward flows), occurring first at 26N and less than a year later at 16N.

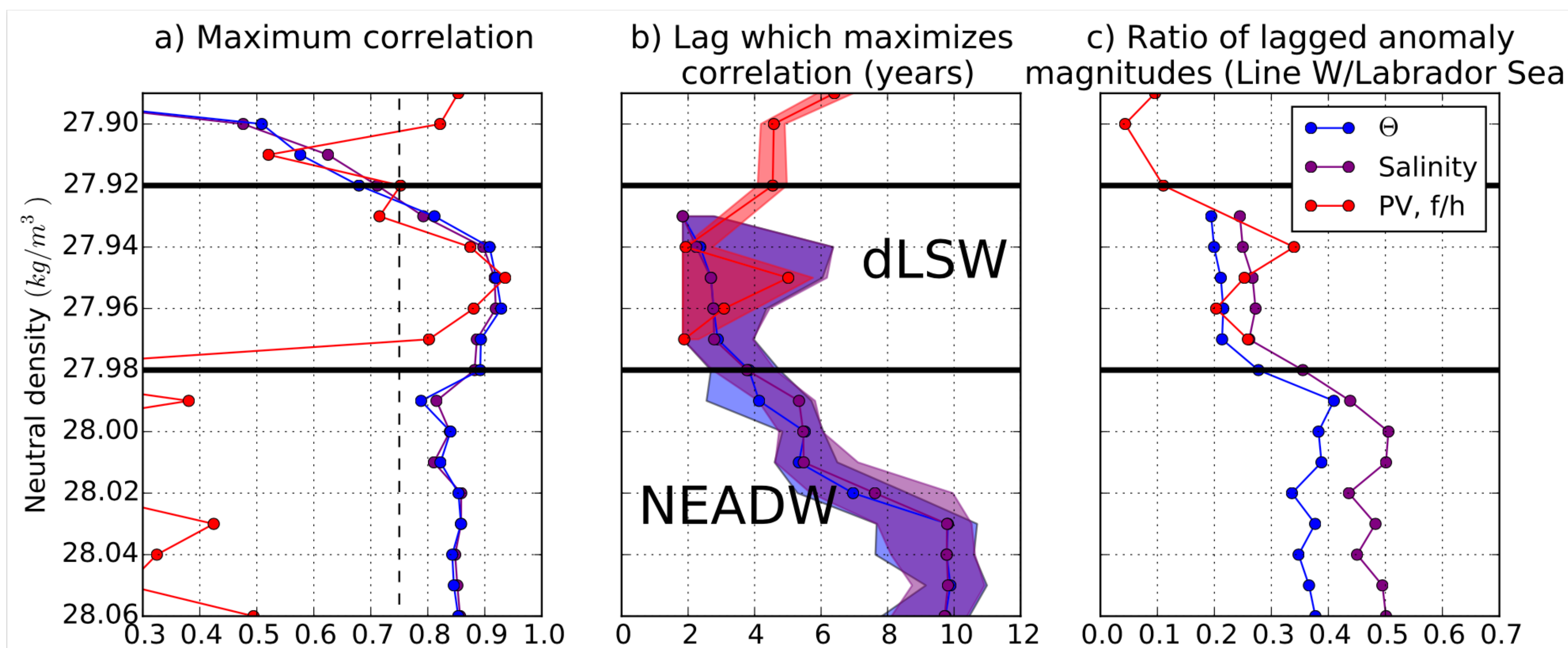


Coherence by advection

LeBras et al. 2017



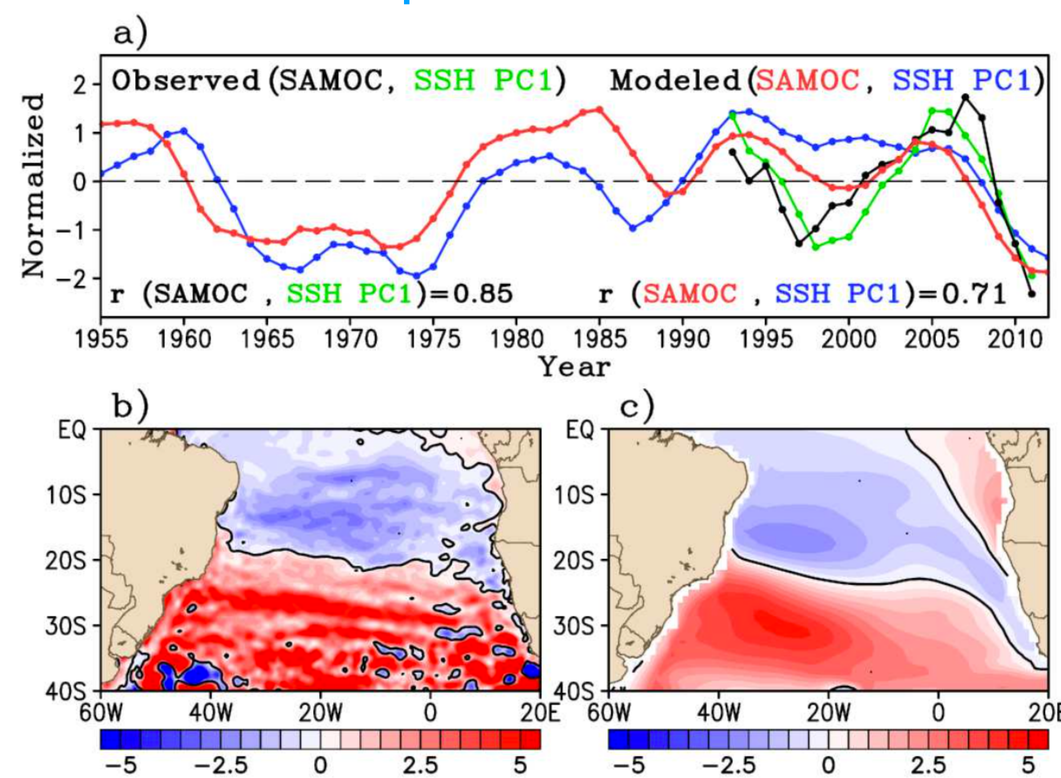
Arrival times of 3 to 7 years from Labrador Sea (55 N) to Line W (39 N)



AMOC:
Climate and Weather

AMOC and Sea Level

Lopez et al. 2016



Frajka-Williams 2015

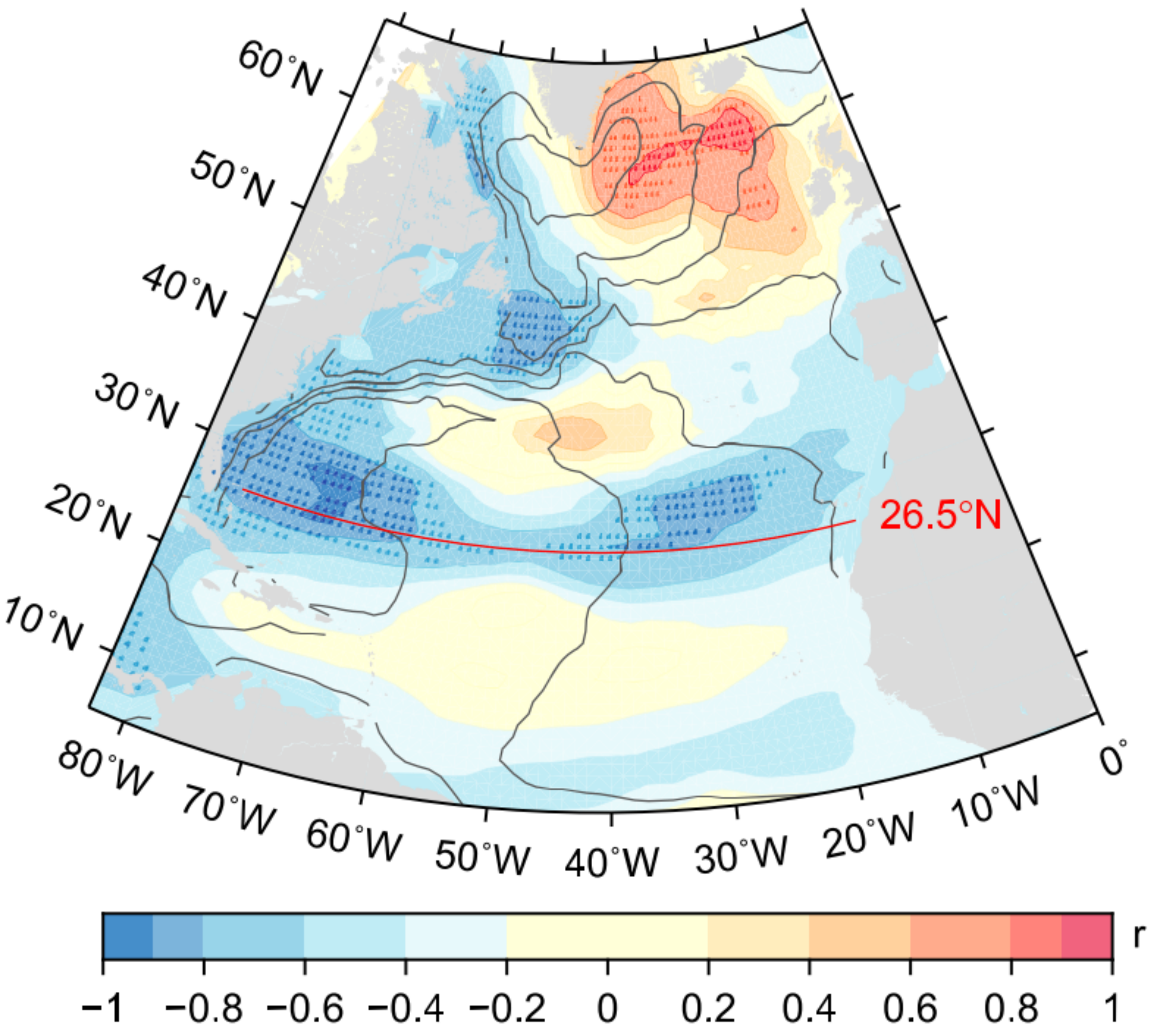
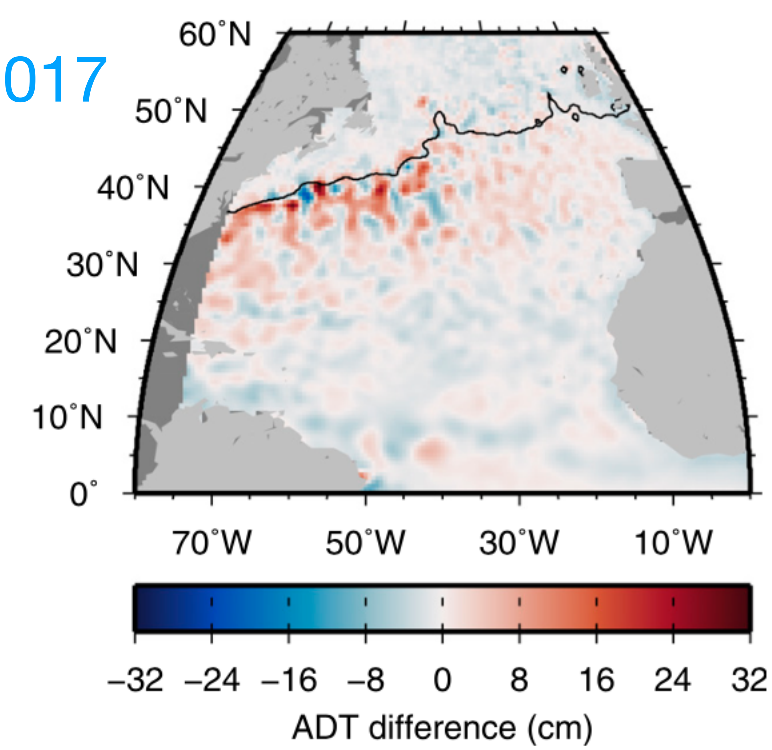


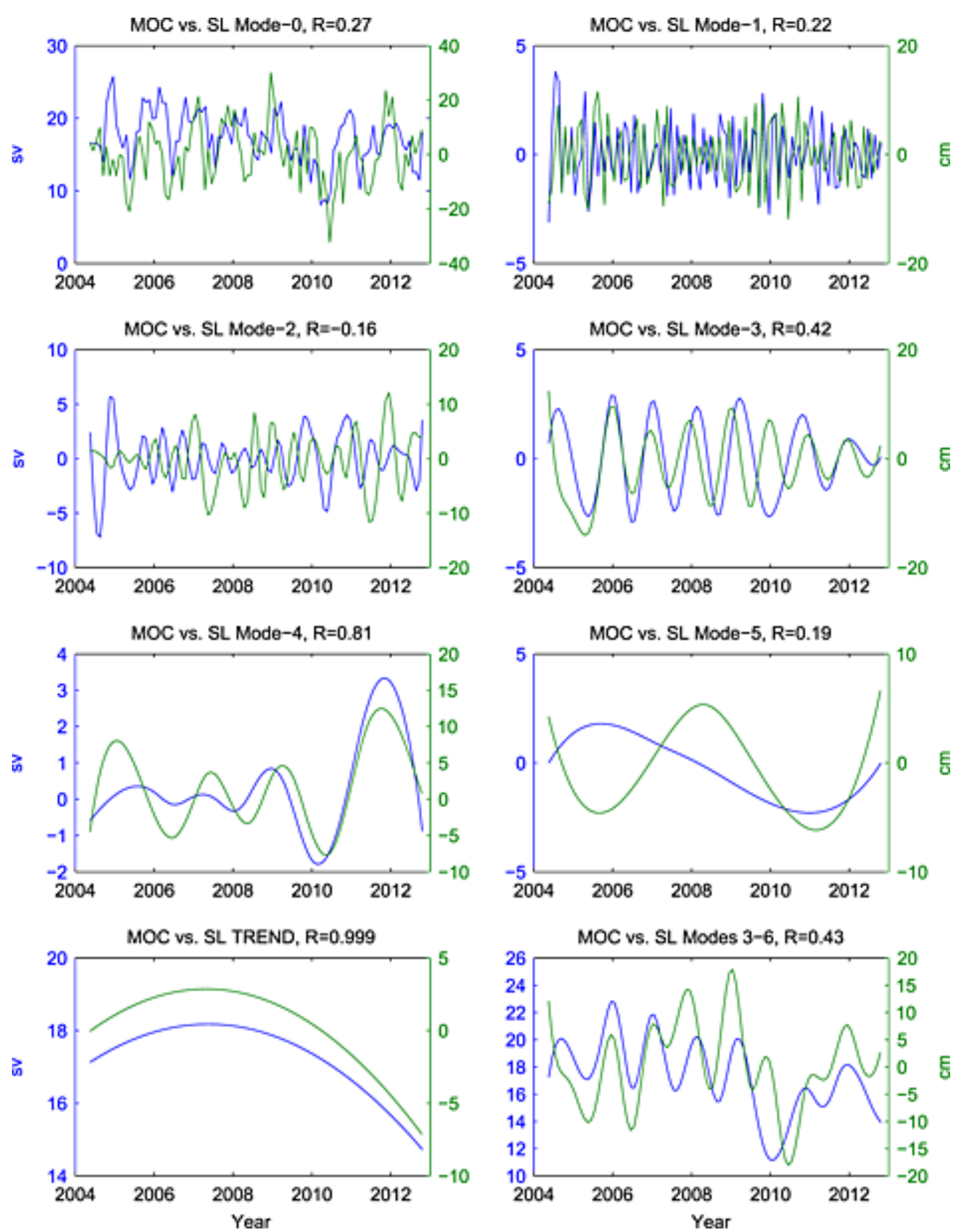
Figure 2. Correlation coefficient between SLA and upper mid-ocean transport at 26.5°N. Red indicates positive correlation, and blue negative. Stippled regions are significant at the 95% level. Mean dynamic ocean topography is overlaid with black contours (contour interval, 20 cm).

Elipot et al. 2017



AMOC and Sea Level

Very weak observational link between sea level differences from tide gauges and 26 N MOC

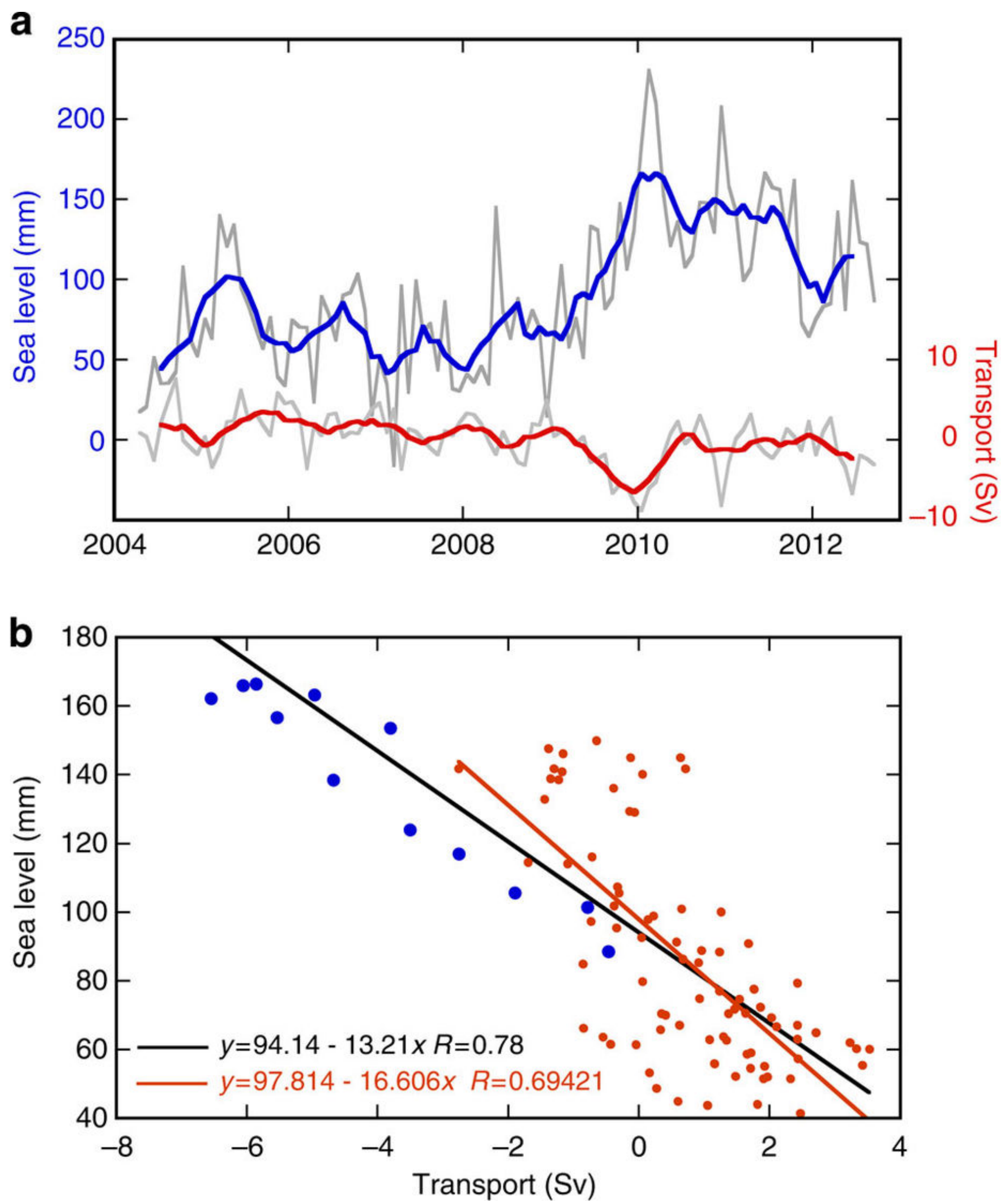


Ezer 2013

Empirical Mode Decomposition analysis of the Meridional Overturning Circulation (MOC) [*McCarthy et al.*,] time series (blue lines; units in sverdrups on the left) and sea level (SL) difference between Bermuda and Atlantic City (green lines; units in centimeters on the right); *R* is the correlation coefficient between MOC and SL. Mode 0 is the original monthly data, and modes 1–5 are oscillating modes with decreasing frequency. (bottom left) Residual trend (mode 6). (bottom right) Sum of modes 3–6.

AMOC and Sea Level

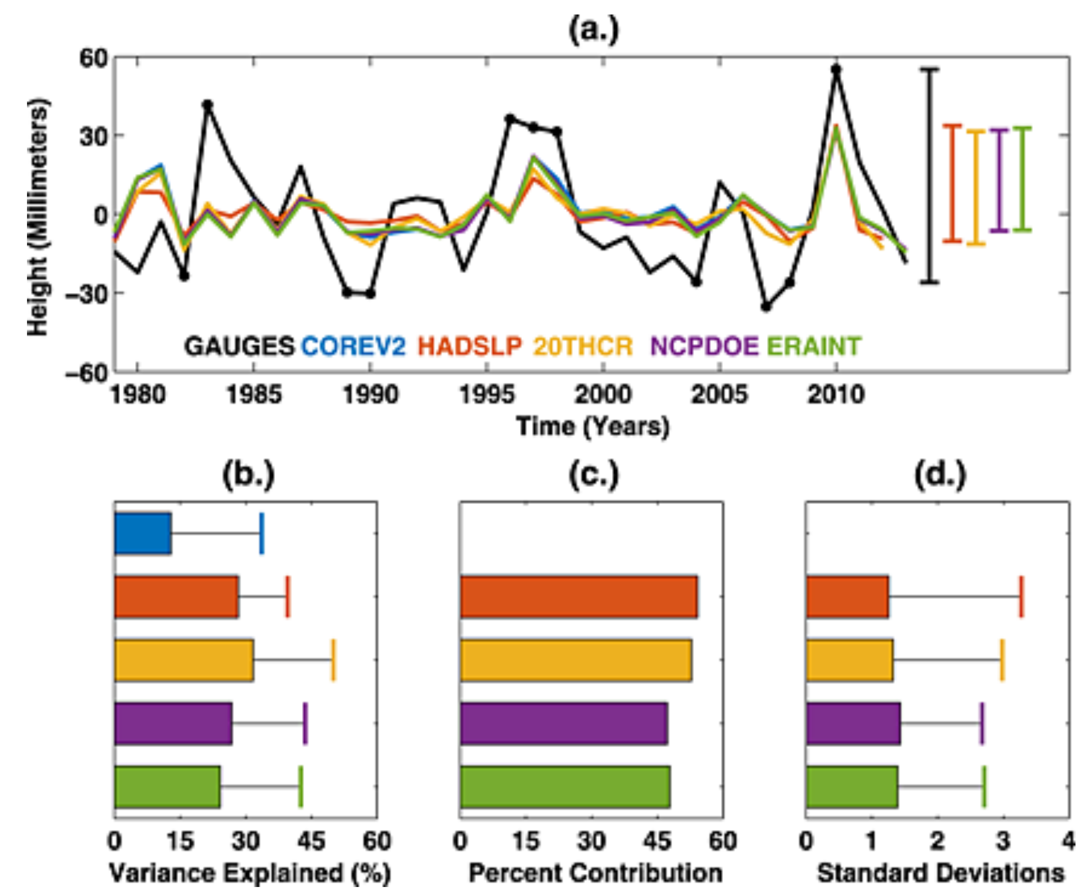
Goddard et al. 2015



26N AMOC versus coastal sea level composite north of NYC: large upswing in 2009-2010 partly associated with AMOC downturn

BUT

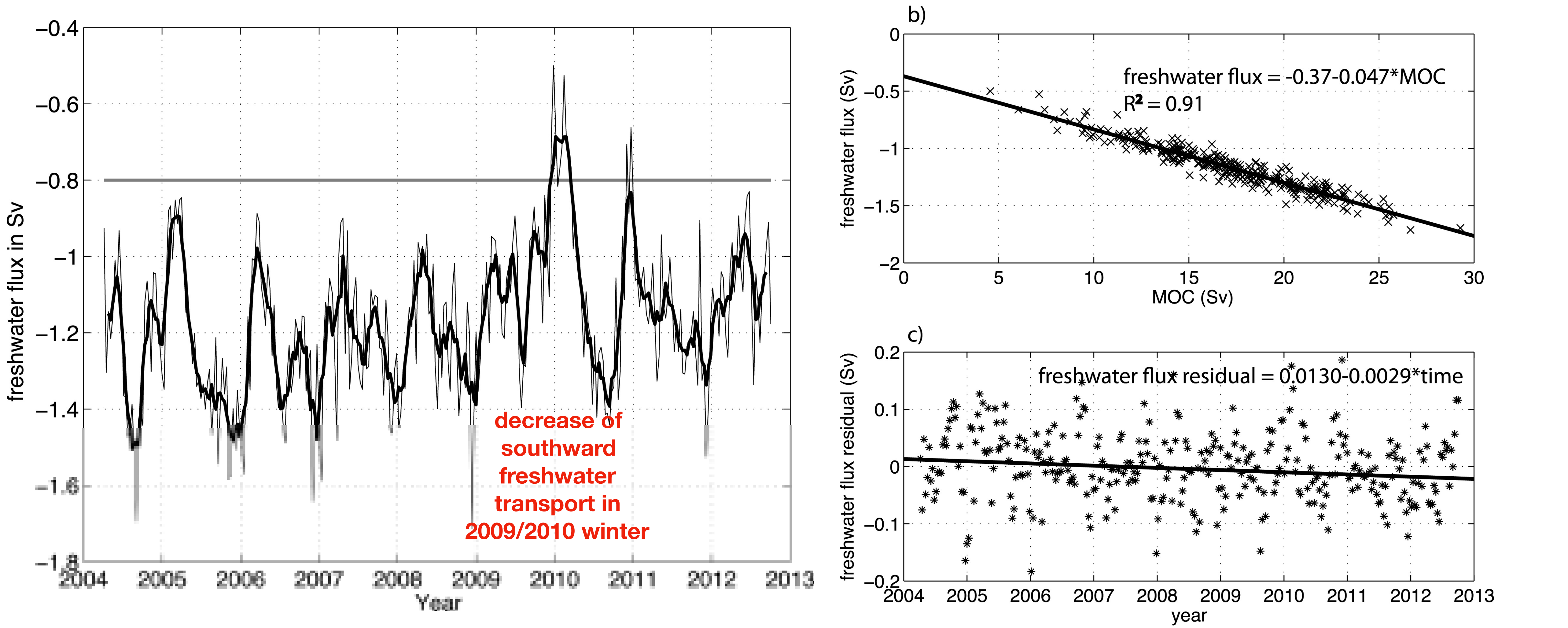
Piecuch and Ponte 2015
showed it is mostly due to Inverse Barometer effect



AMOC and freshwater flux

McDonagh et al 2015, Continuous Estimate of Atlantic Oceanic Freshwater Flux at 26.5°N

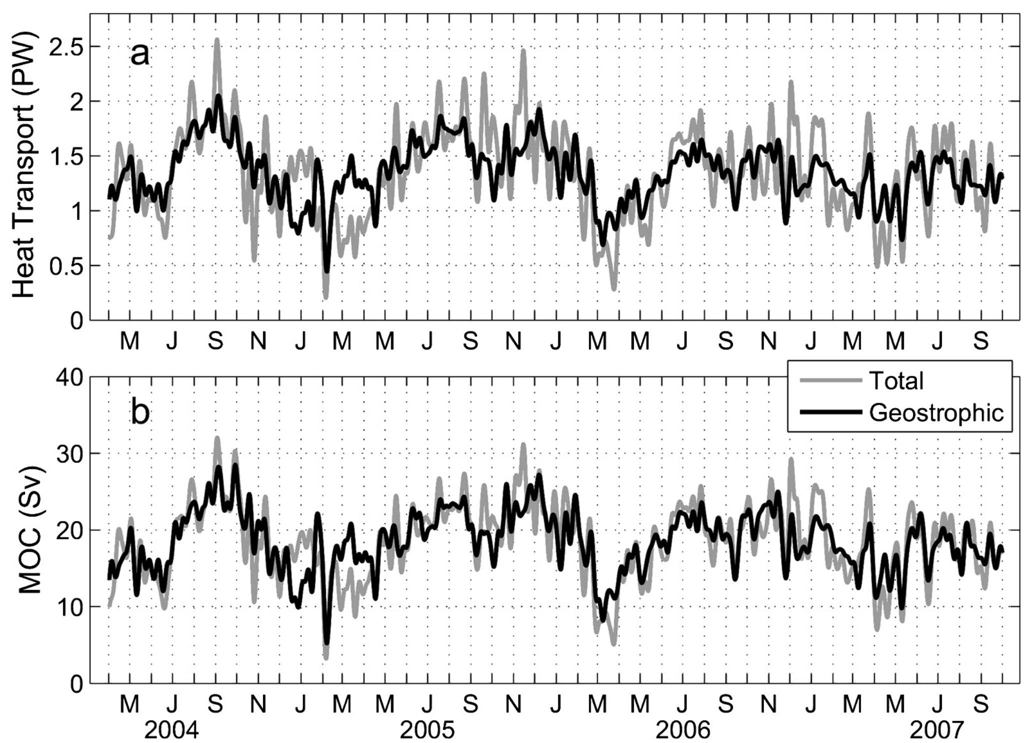
26 N RAPID-MOCHA-WBTS + Argo : mean and std: -1.17 +/- 0.20 Sv, southward. Implies divergence of -0.37 +/- 0.20 Sv, into the ocean. Dominant component of variability is MOC. MOC transport explains 91% of the variance of the freshwater flux.

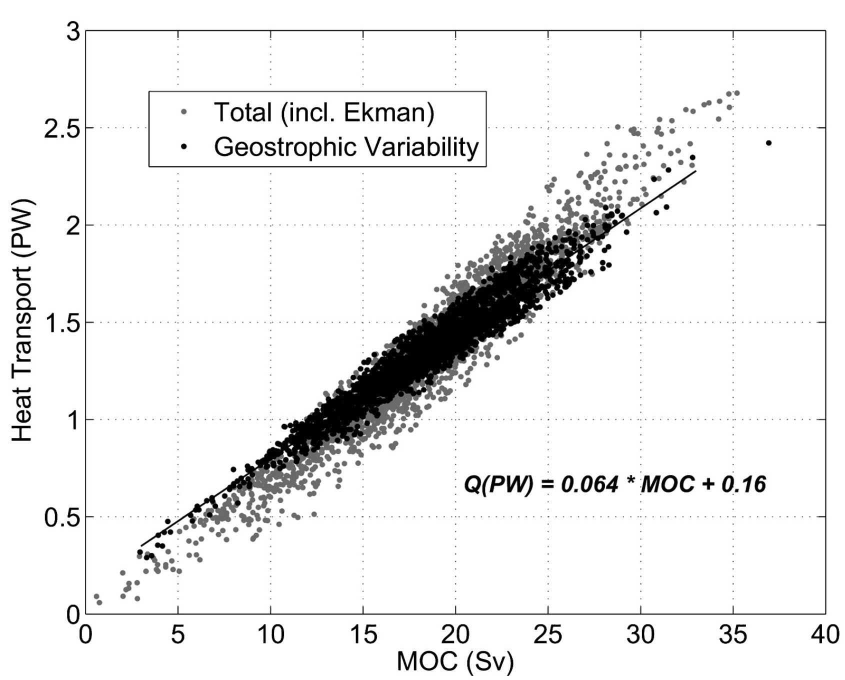


AMOC and heat flux

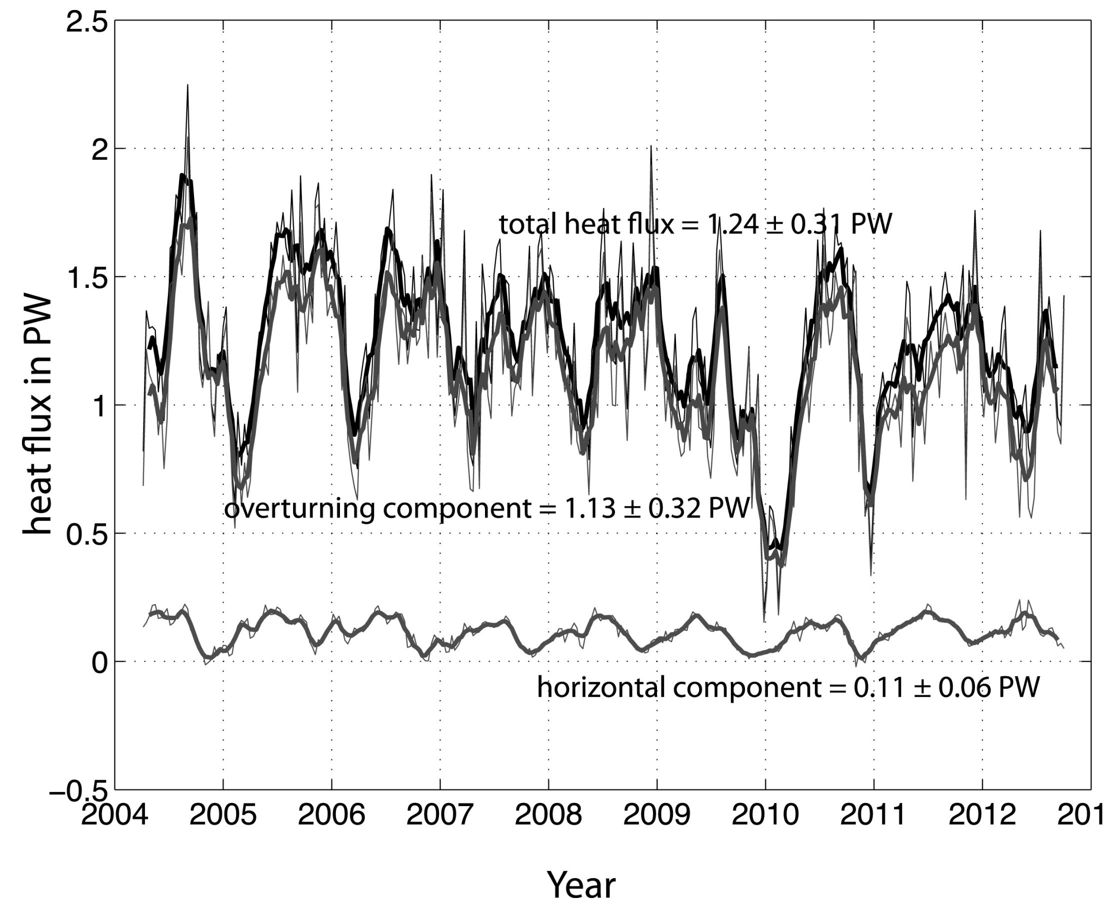
26 N

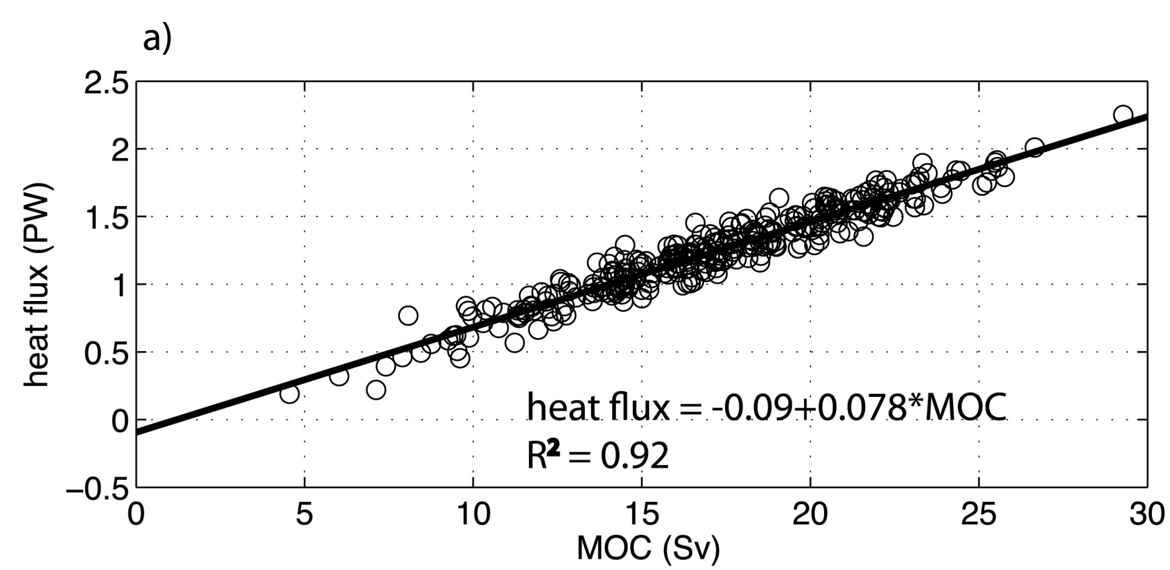
Johns et al. 2011





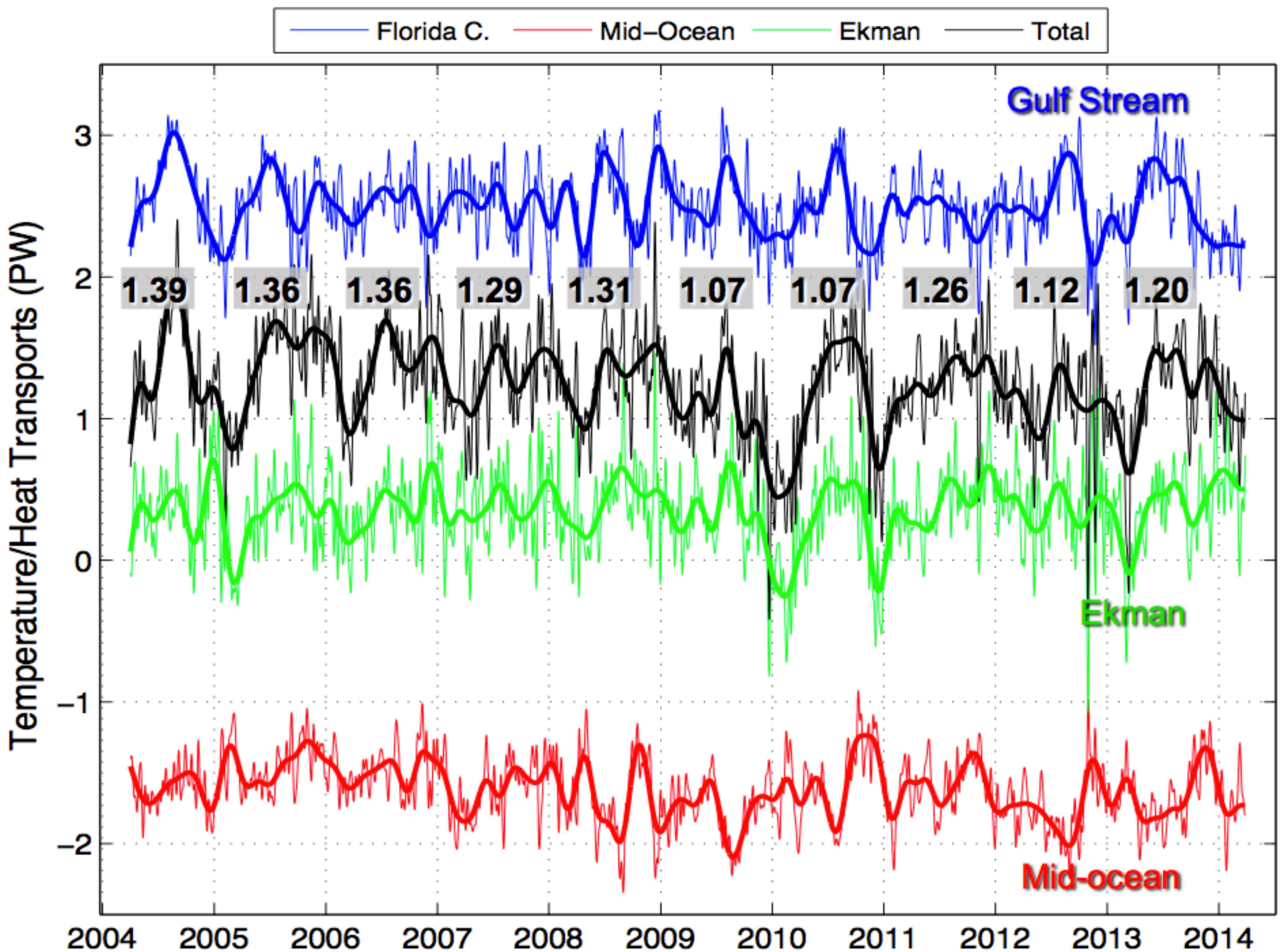
McDonagh et al. 2015



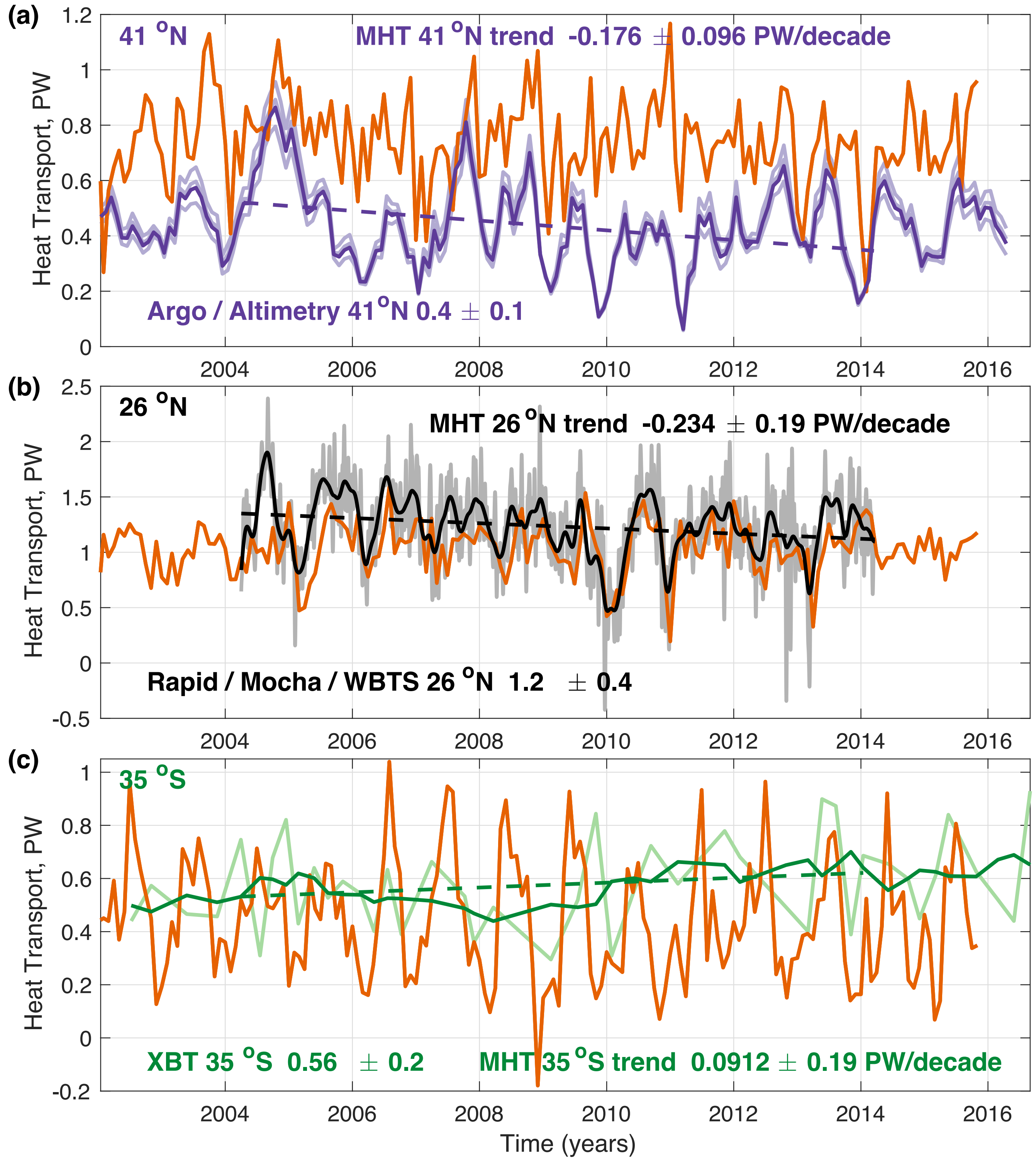


AMOC and heat flux

26 N



AMOC and heat flux



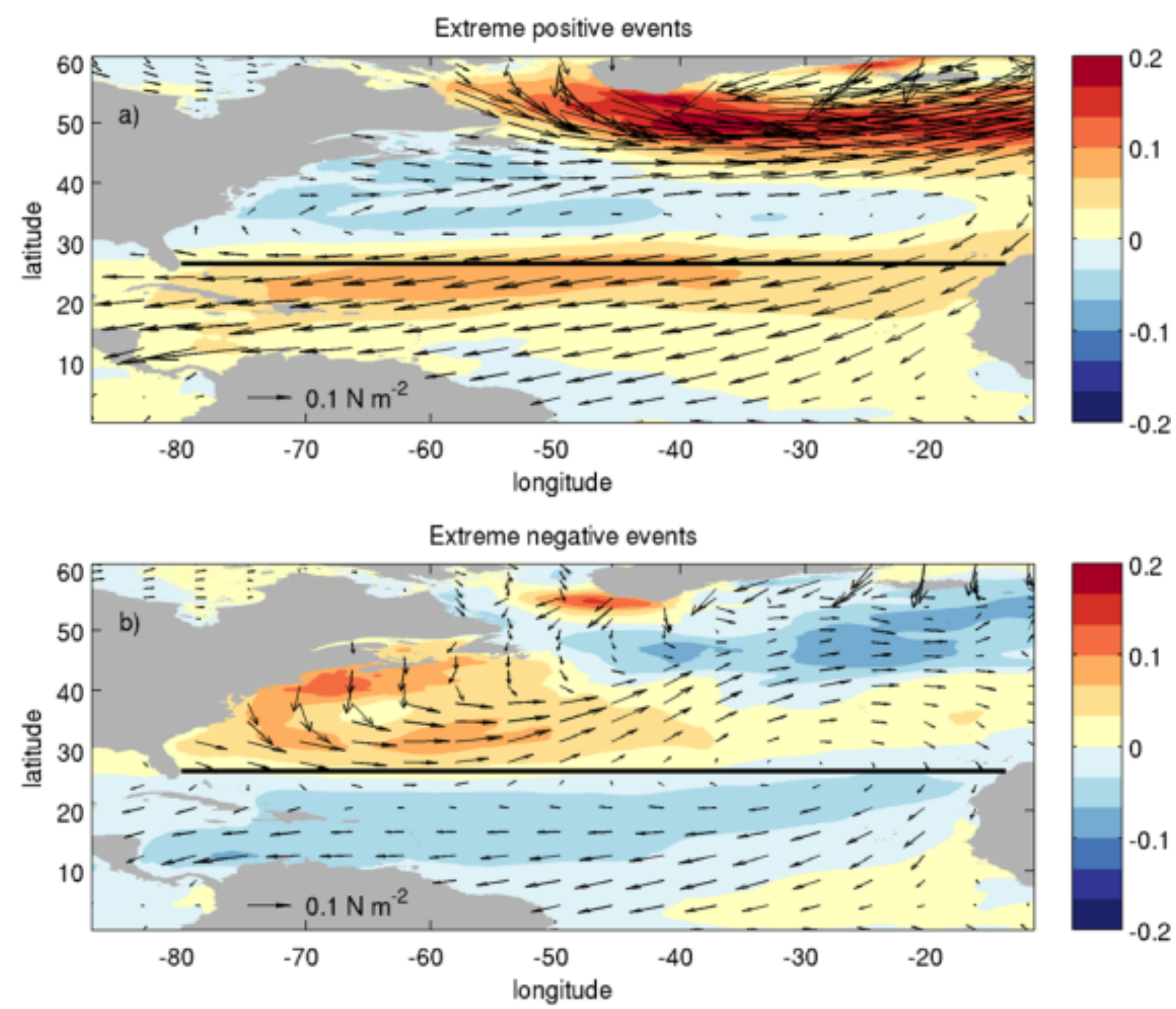
orange lines show ECCO2-derived fluxes

BAMS State of the Climate 2016

AMOC and heat flux

Moat et al. (2015) Major variations in subtropical North Atlantic heat transport at short (5 day) timescales and their causes

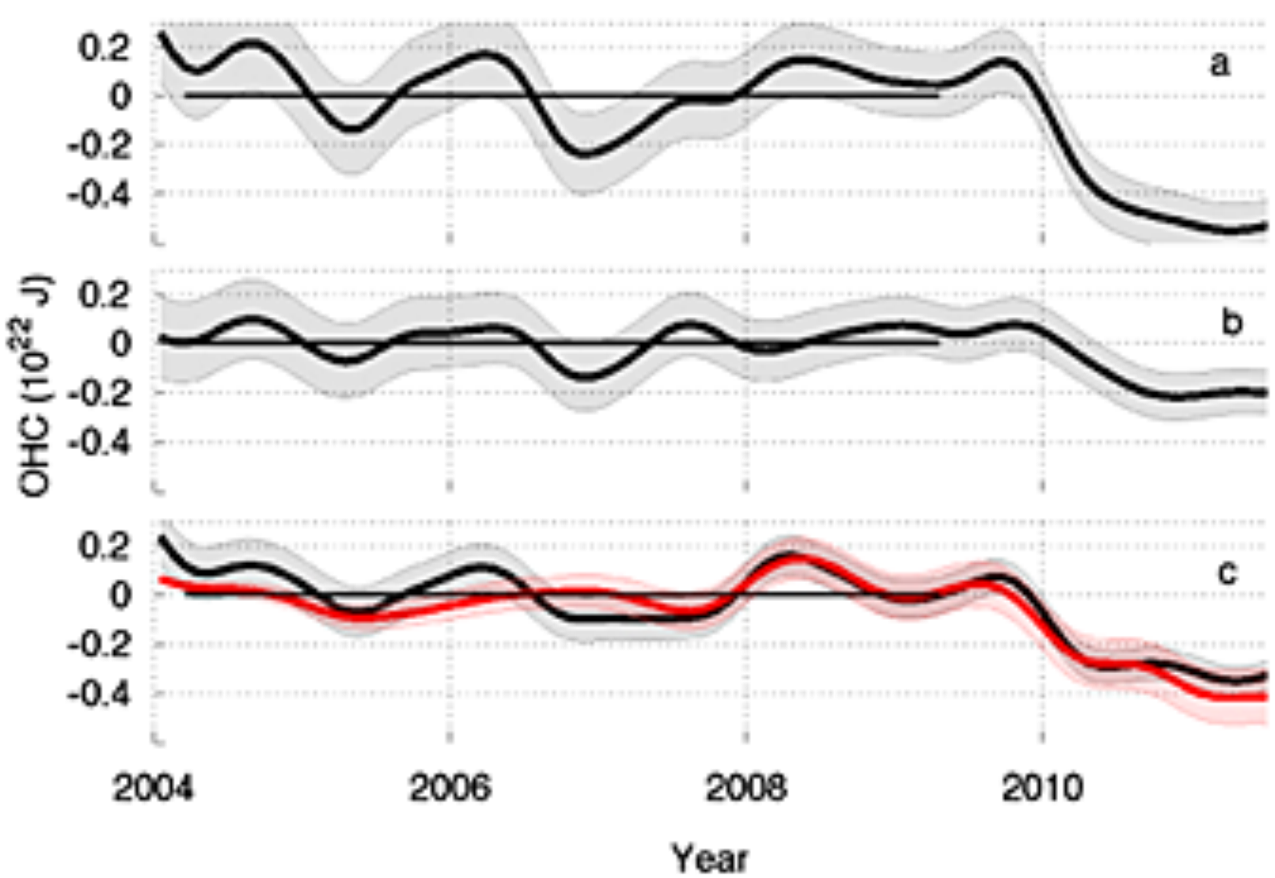
5 day timescales the largest changes in the heat transport across 26.5°N coincide with north-westerly airflows originating over the American land mass that drive strong southward anomalies in the Ekman flow. During these events the northward heat transport reduces by 0.5–1.4 PW. (mean is 1.24±0.36 PW)



AMOC and fluxes: impact

Cunningham et al. 2013, Atlantic Meridional Overturning Circulation slowdown cooled the subtropical ocean

Ocean heat content, in the subtropical Atlantic, is strongly influenced by interannual variability of the AMOC. Their analysis suggests that ocean advection played a significant role in driving the negative temperature anomalies of the seasonally mixed layer in the subtropical Atlantic during 2010.



Relative heat content changes between 26.5N and 41N

From volume change (divergence)

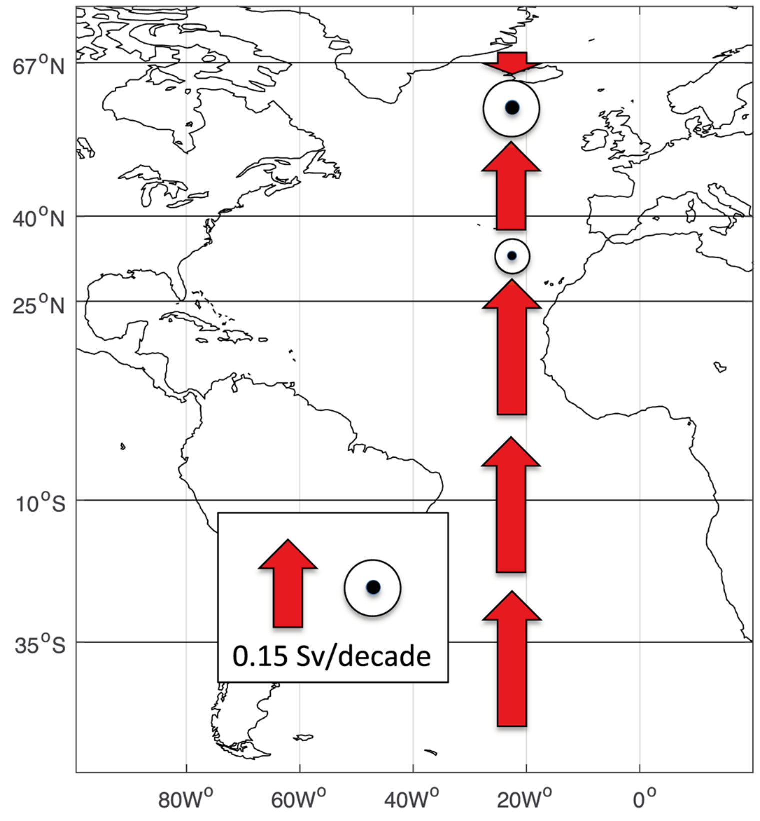
From temperature change (air-sea fluxes in red)

Fluxes and AMOC: impact

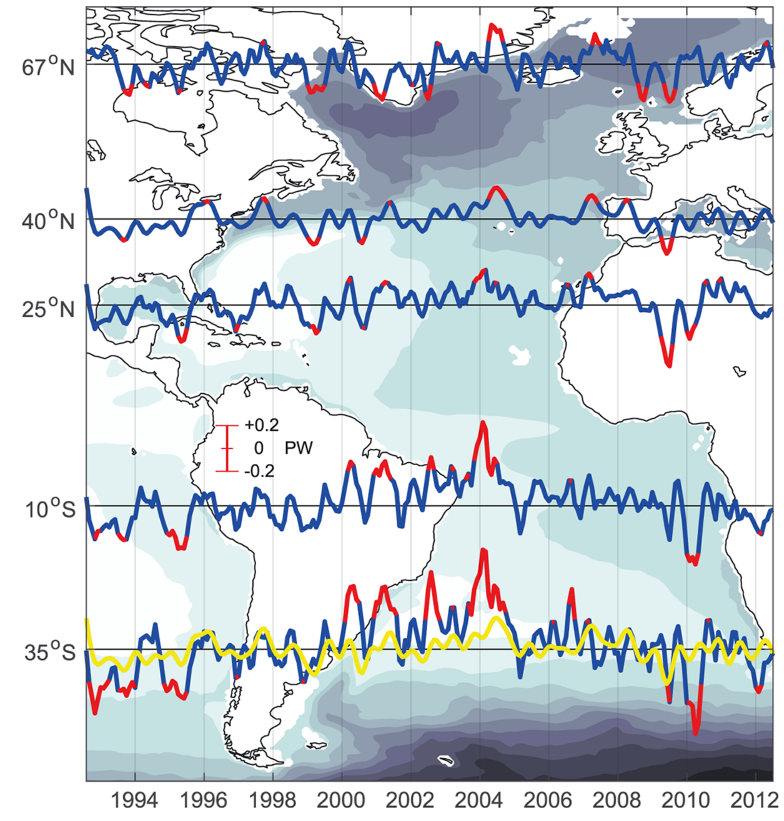
Kelly et al. 2016, Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports

During the AMOC slowdown (2004–2012) northward transport of heat and southward transport of freshwater decrease with a high degree of spatial coherence throughout the Atlantic.

> "Weaker trends in the North Atlantic result in freshwater convergence there; however, salinity remains high because freshwater flux is decreasing. The coincidence of high salinity and a slowdown of the AMOC supports recent modeling studies that suggest that heat, not freshwater, drives anomalies in the strength of the AMOC in a warming ocean"



Trends in freshwater budget for 2004–2012. Trends in freshwater transport (arrows) and convergence (FWC, dots) across the boundaries and within four regions



Meridional heat transport anomalies from the box model (blue) at 67°N, 40°N, 25°N, 10°S, and 35°S. MHT at 41°N derived from estimates by *Willis* [2010] is repeated (yellow) at 35°S for comparison.

AMOC and weather extremes

Srokosz and Bryden 2015

Bryden et al. 2014

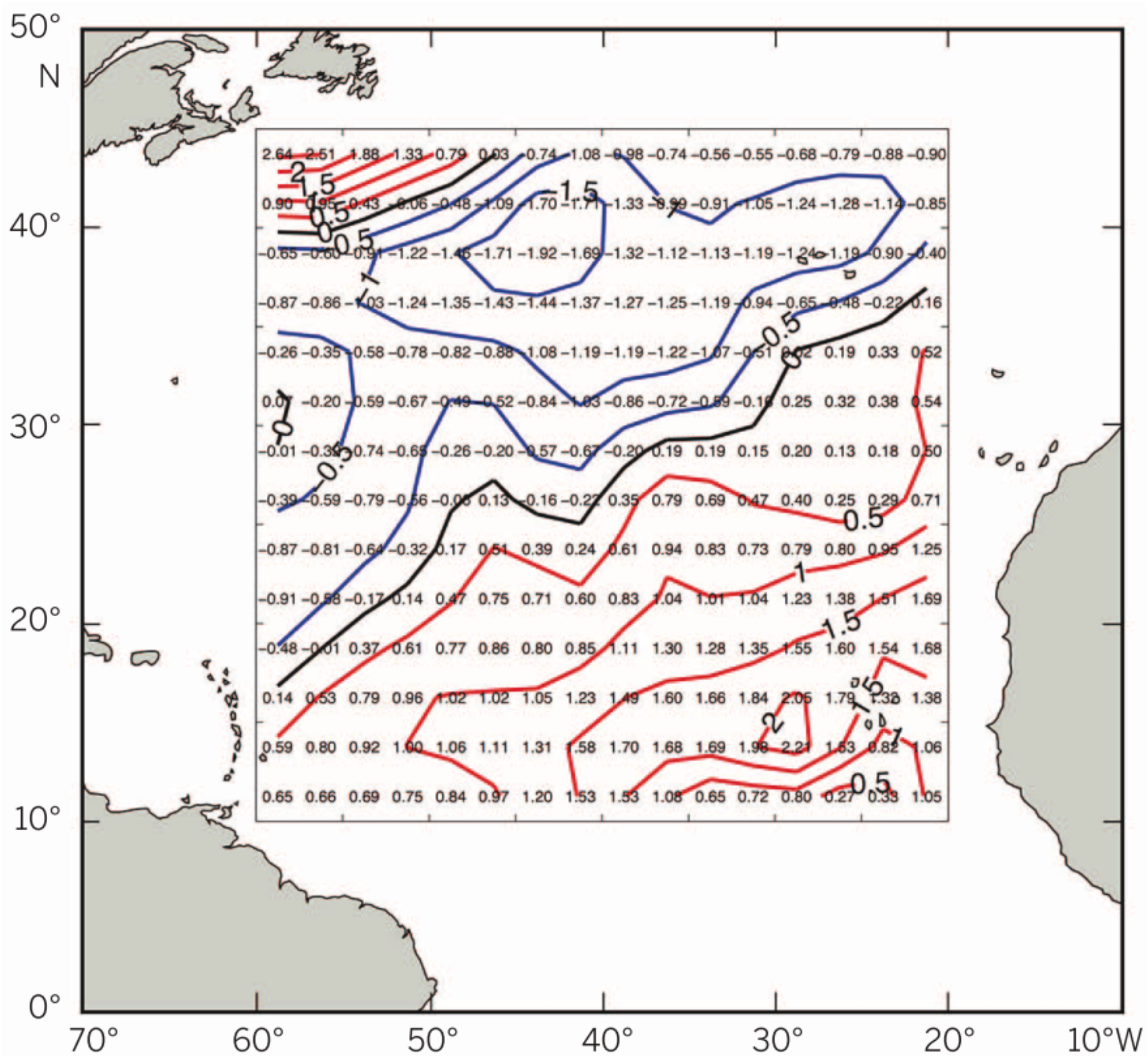


Fig. 3. North Atlantic temperature anomaly (°C) at 50-m depth, averaged for May to July 2010 at the end of the 2009–2010 AMOC slowdown event (93). Temperature data are from Argo floats, and the anomaly is calculated relative to the Hydrobase seasonal climatology. Note the cooling (blue contours) of the upper ocean to the north and warming (red contours) to the south of 26.5°N, the latitude of the RAPID observations and of the maximum northward heat transport by the Atlantic.

"arguably contributed to the intensity of the 2010 Atlantic hurricane season that was the strongest since 2005."

AMOC and its climate interactions from observations: gaps? challenges? questions? ideas?

(from 2017 US AMOC meeting highlights)

- Understanding of meridional/latitudinal coherence (or lack of) is still a priority.
- Continuation of existing observational array?
- Accessibility of data need to be improved (not all time series are actually available). New data products?
- AMOC metrics for observations/model comparisons?
- **from Task Team 2: "Observational studies should focus on mechanisms and pathways that identify and explain coherent and incoherent signals between different study sites, thereby reaching consensus on which signals represent the large-scale AMOC versus more localized circulation patterns."**
- AMOC and dynamical (coastal) sea level? Is there really observational evidence?
- **Recast of TT4 priorities in terms of interactions between various components of the climate system and the AMOC**; include AMOC and ITCZ? AMOC and hydrological cycles (including clouds)? AMOC and climate/weather extremes?