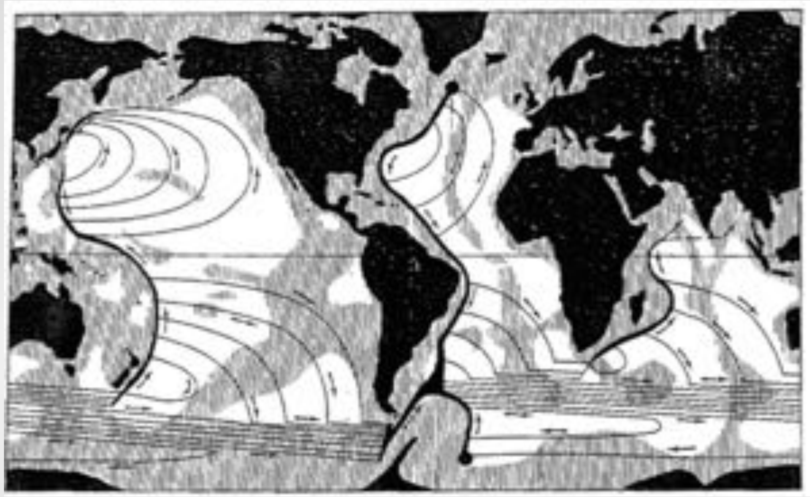
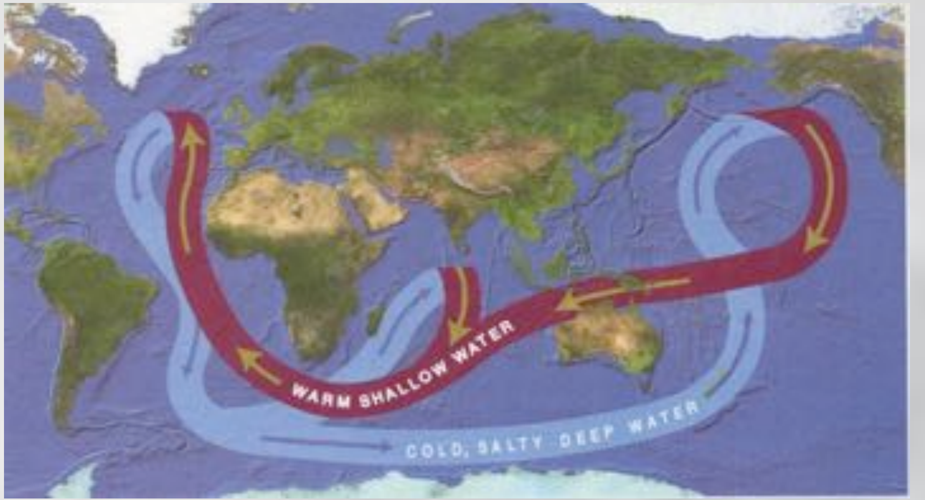
Observed Meridional Overturning Circulation transport variability in the North and South Atlantic: Recent results on structure, time scale, and amplitude

Christopher S. Meinen
NOAA-Atlantic Oceanographic and Meteorological Laboratory

(with input and help from many others!)



Stommel, 1958



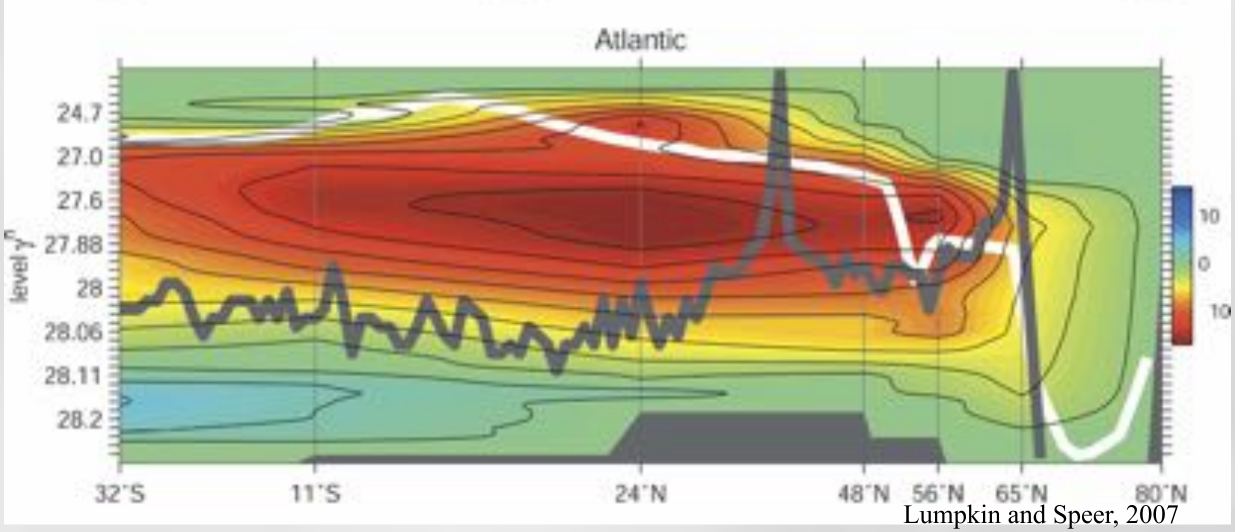
Modified from Broecker, 1987 (From Columbia Univ. web page)

Important note: The work presented here has been supported by multiple funding agencies in many countries, and this international support of ongoing MOC studies is essential!

Acknowledgement: Funding from NOAA Climate Program Office – Ocean Observing and Monitoring Division and by the NOAA Atlantic Oceanographic and Meteorological Laboratory.

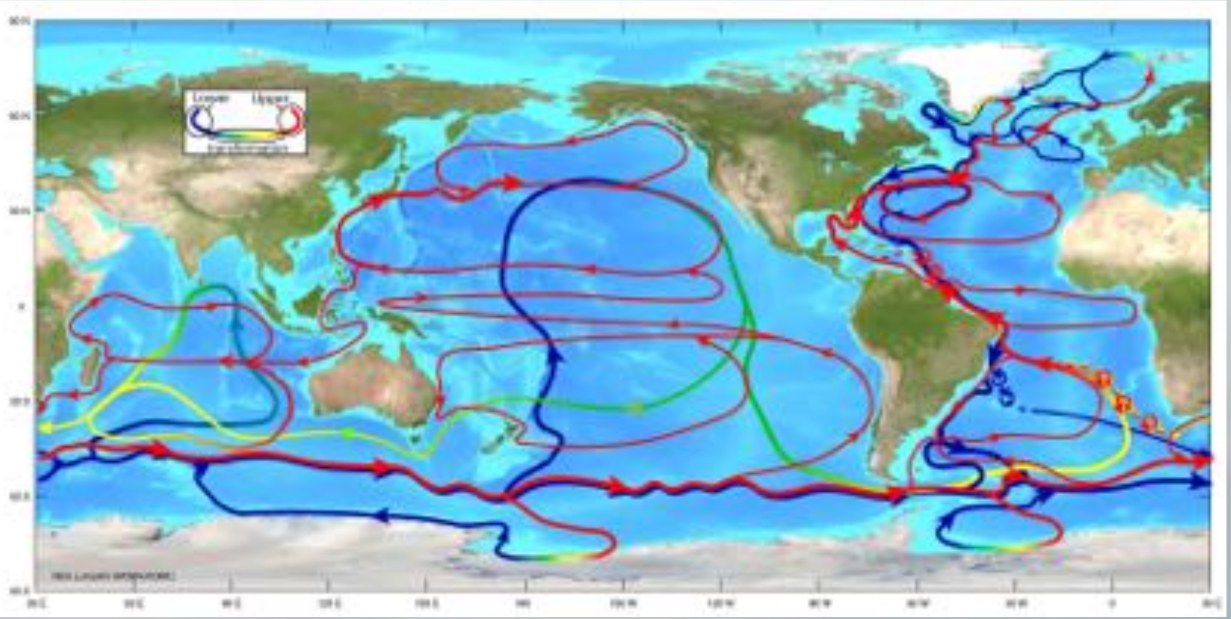
What is the Meridional Overturning Circulation (MOC)?

At it's simplest, perhaps we can call the MOC a component of the global ocean circulation system that connects sinking waters in the high latitudes, slow upwelling waters around the globe, and waters toward (at/near the surface) and away (at great depth) from the sinking regions.



Lumpkin and Speer, 2007

While the "meridional" in the name refers to north-south motions, in reality we know that is an oversimplification, with significant east-west components to the circulation as the waters are exchanged between basins (such as in the Southern Ocean) and within the basins.



So why do we care about the MOC?

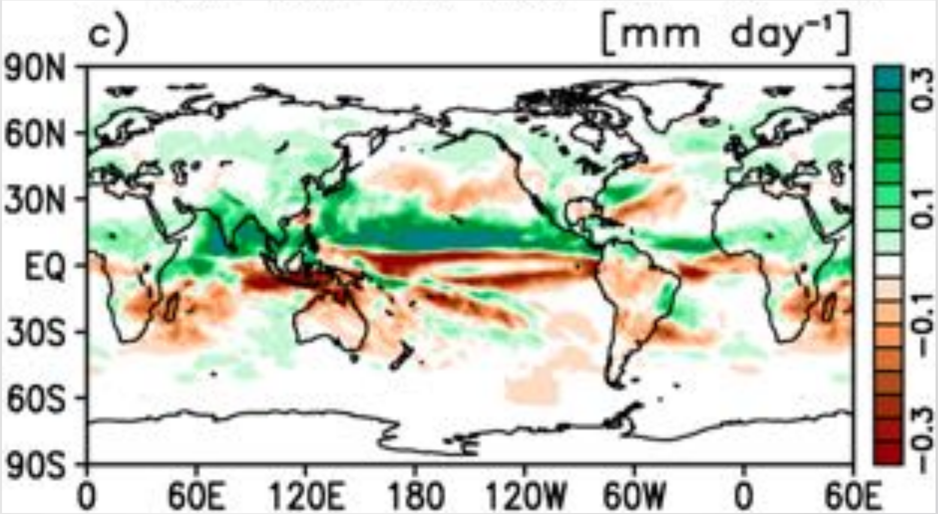
The MOC is one of the primary mechanisms through which the ocean moves heat, salt, and carbon within and between ocean basins.

Why does that matter to folks here in Miami, for example?

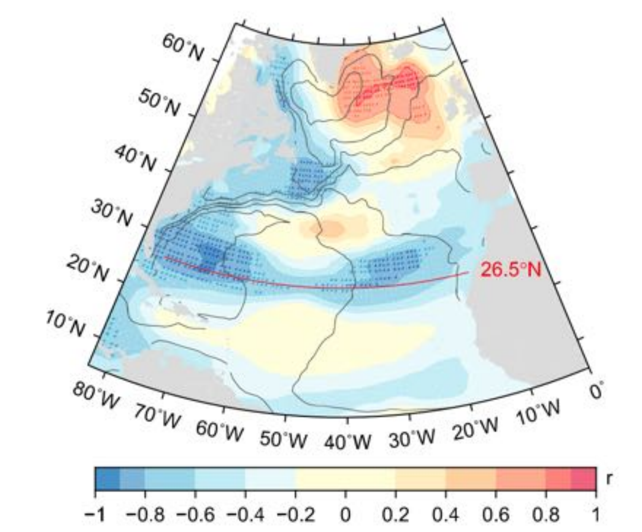
If the MOC changes, the SST in the North Atlantic offshore will change – which changes the wind shear – which affects the formation and evolution of hurricanes.

Variations in MOC are related to more than just hurricane intensification.

Numerical models also suggest that changes in the MOC are related to changes in more things we care about, such as precipitation patterns (see example above), droughts, heat waves, sea level changes, and more.

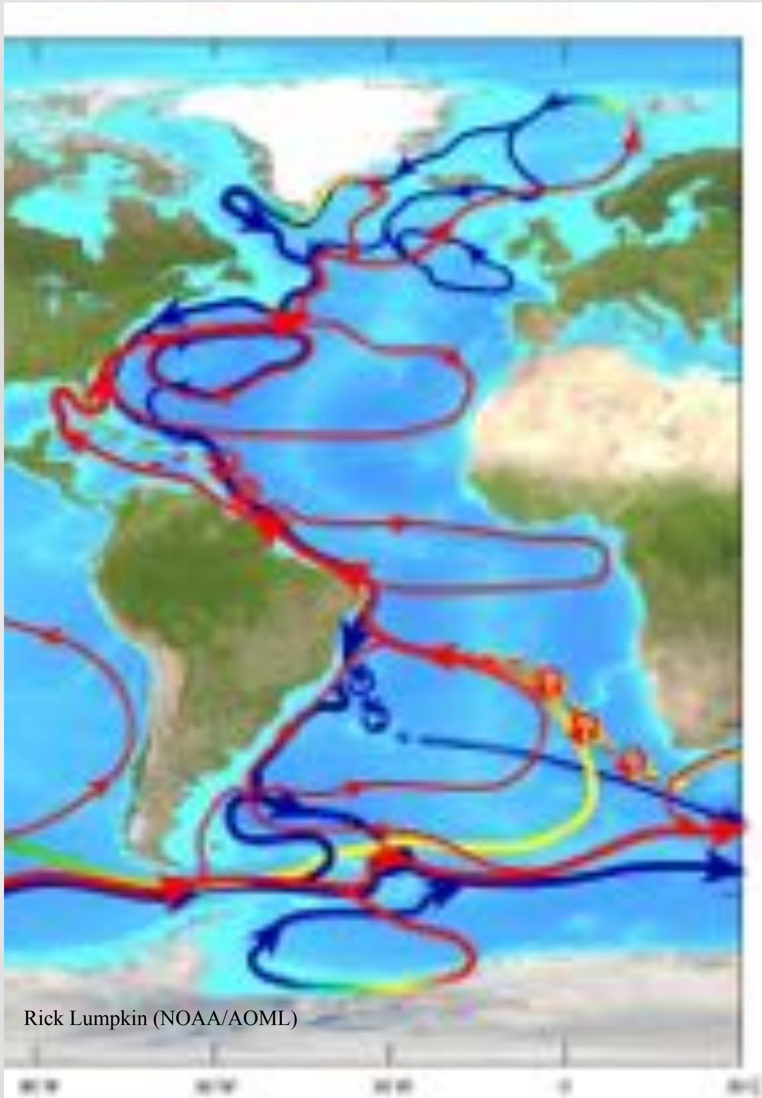


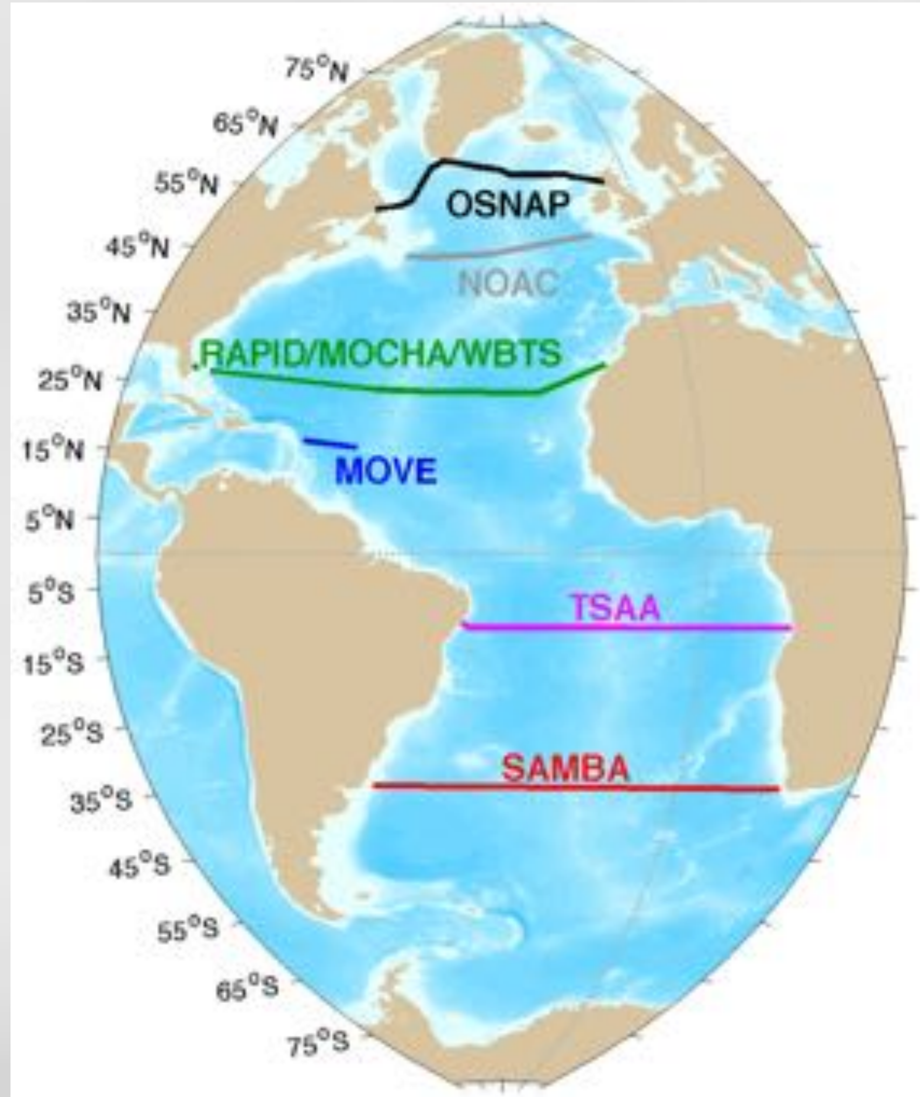
Composited difference of precipitation corresponding to weak minus strong South Atlantic meridional heat transport 20-years after the SAMHT anomaly. Modified from Lopez et al. (2016).



Correlation coefficient between sea level anomaly and upper-mid ocean transport at 26.5°N. Red indicates positive, blue negative; stippled regions are significant at 95%. Mean dynamic topography overlaid as black contours. From Frajka-Williams (2015).

Observing the Meridional Overturning Circulation (MOC)

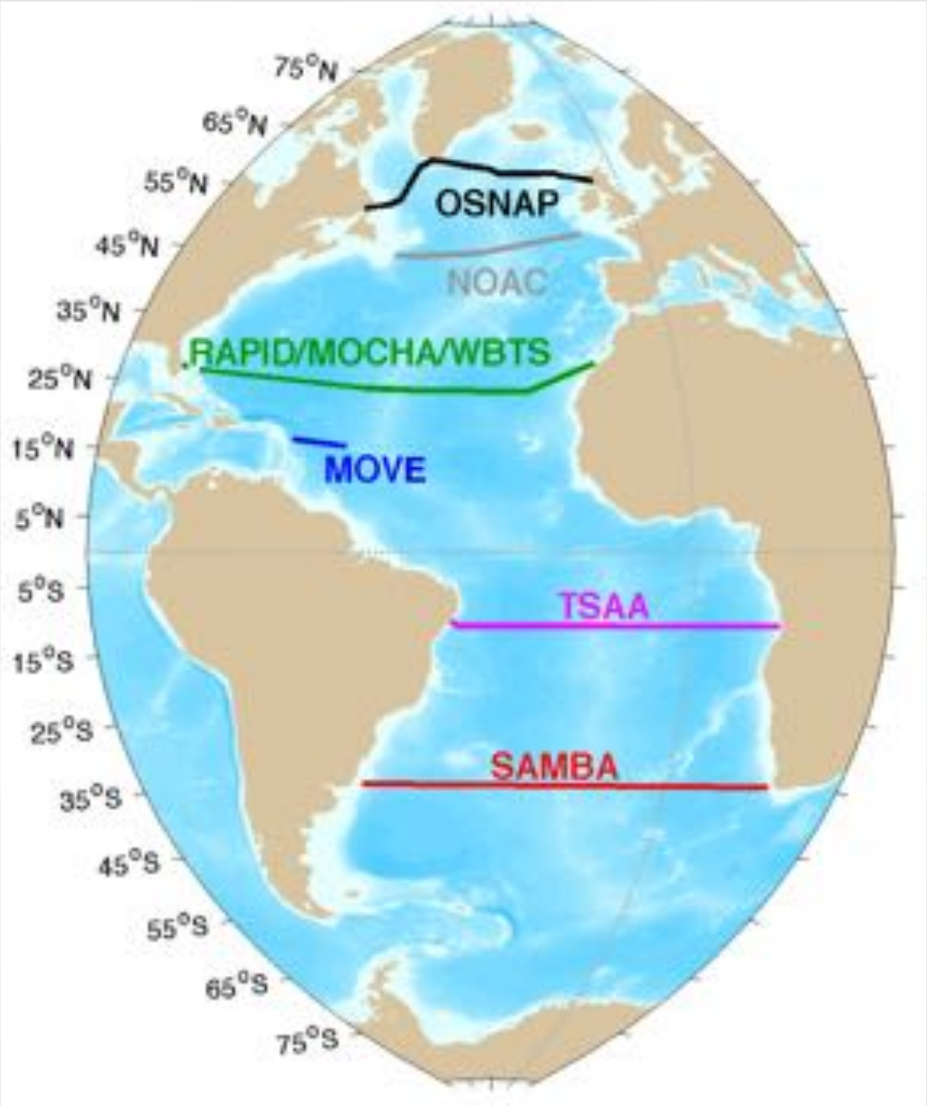




Six MOC arrays providing continuous (~daily) observations, each with their own strengths and limitations.

We're also getting MOC estimates from trans-basin ship sections (CTD, XBT), Argo, and satellite observations, each with its own time scale (e.g. snapshot, monthly, quarterly) and accuracy.

Observing the Meridional Overturning Circulation (MOC), continued



OSNAP
- In place during September 2014 to present
- More detail in talk by Feili Li & posters

NOAC
- In place during April 2016 to present (Western basin since June 2009)

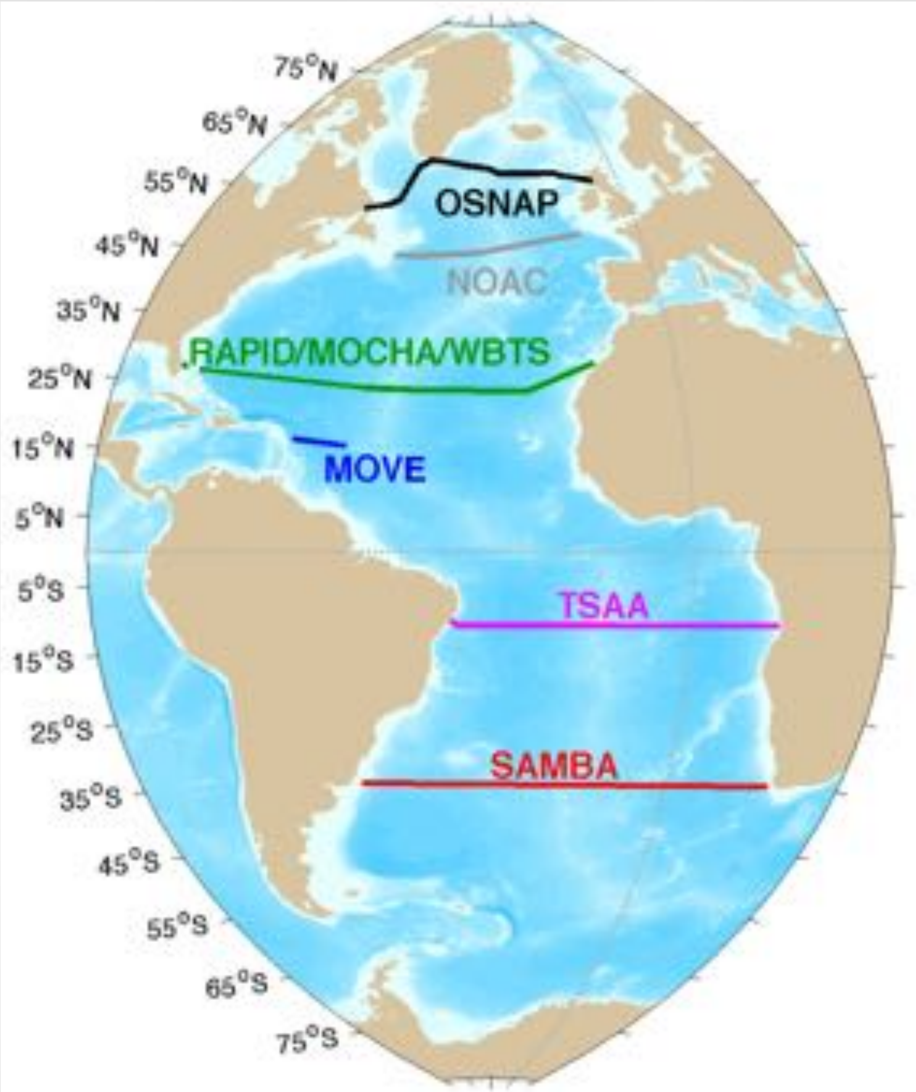
RAPID-MOC/MOCHA/WBTS
- In place during April 2004 to present
- More detail in talks by David Smeed, Elaine McDonagh & posters

MOVE
- In place during February 2000 to present
- More detail in poster by M. Lankhorst

TSAA
- In place during July 2013 to present

SAMBA
- In place during March 2009-December 2010 and September 2013 to present
- More detail in posters by C. Meinen, M. Kersale

Meridional Overturning Circulation (MOC) basic statistics



OSNAP
- Time mean: 13.2 Sv (Sep. 2014 to May 2016)
- Standard deviation: 3.3 Sv

NOAC
- (Coming soon)

RAPID-MOC/MOCHA/WBTS
- Time mean: 17.0 Sv (Apr. 2004 to Feb. 2017)
- Standard deviation: 4.4 Sv

MOVE
- Time mean: 18.0 Sv (Feb. 2000 to Jun. 2018)
- Standard deviation: 5.5 Sv

TSAA
- Time mean: 14.3 Sv (Jul. 2013 to ~Sep. 2016)
- Standard deviation: 2.4 Sv

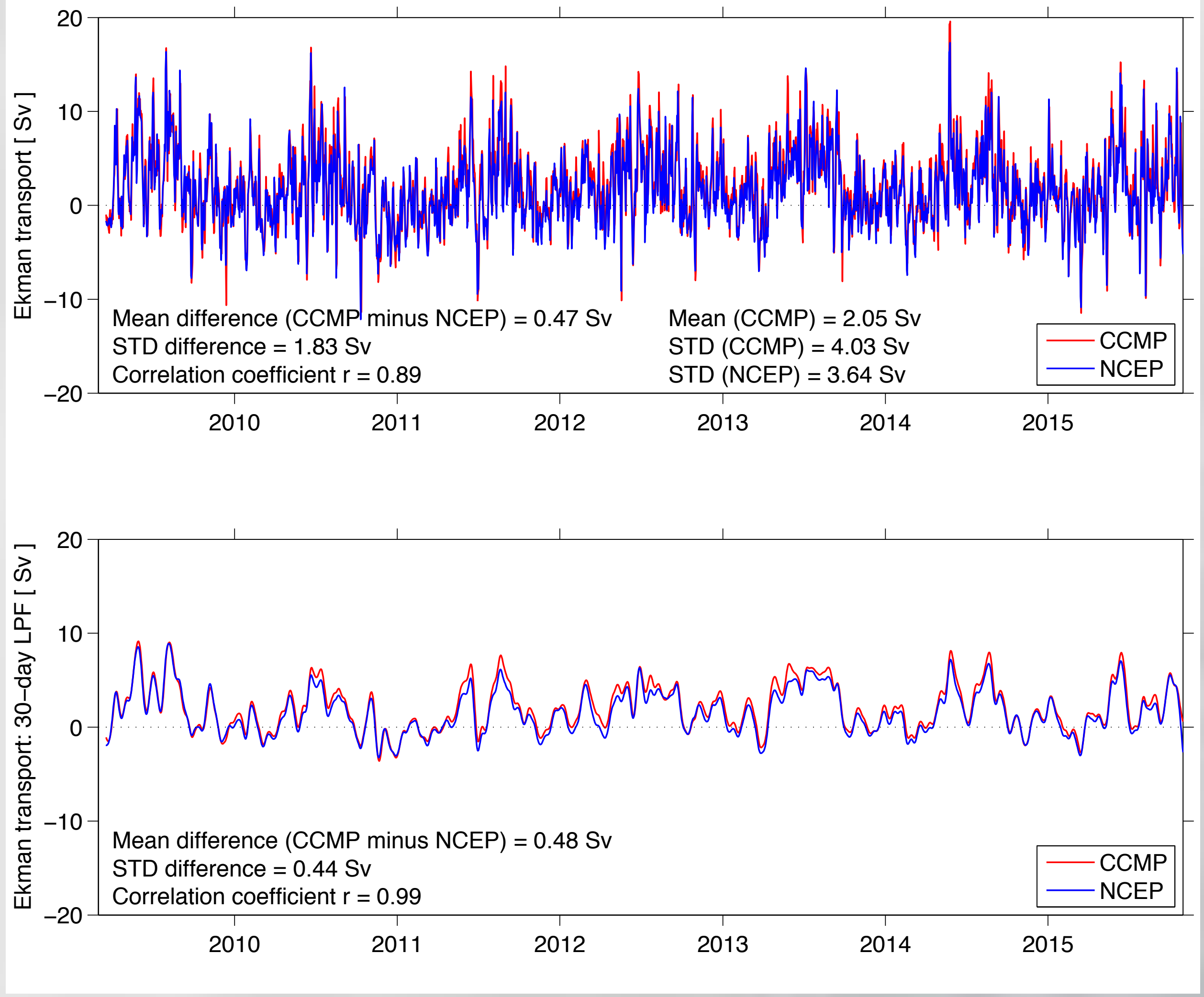
SAMBA
- Time mean: 14.7 Sv (Mar. 2009 to Apr. 2017)
- Standard deviation: 8.3 Sv

Meridional Overturning Circulation (MOC) − caveats regarding comparisons

When we think about comparing our MOC estimates at different latitudes, there are many considerations.

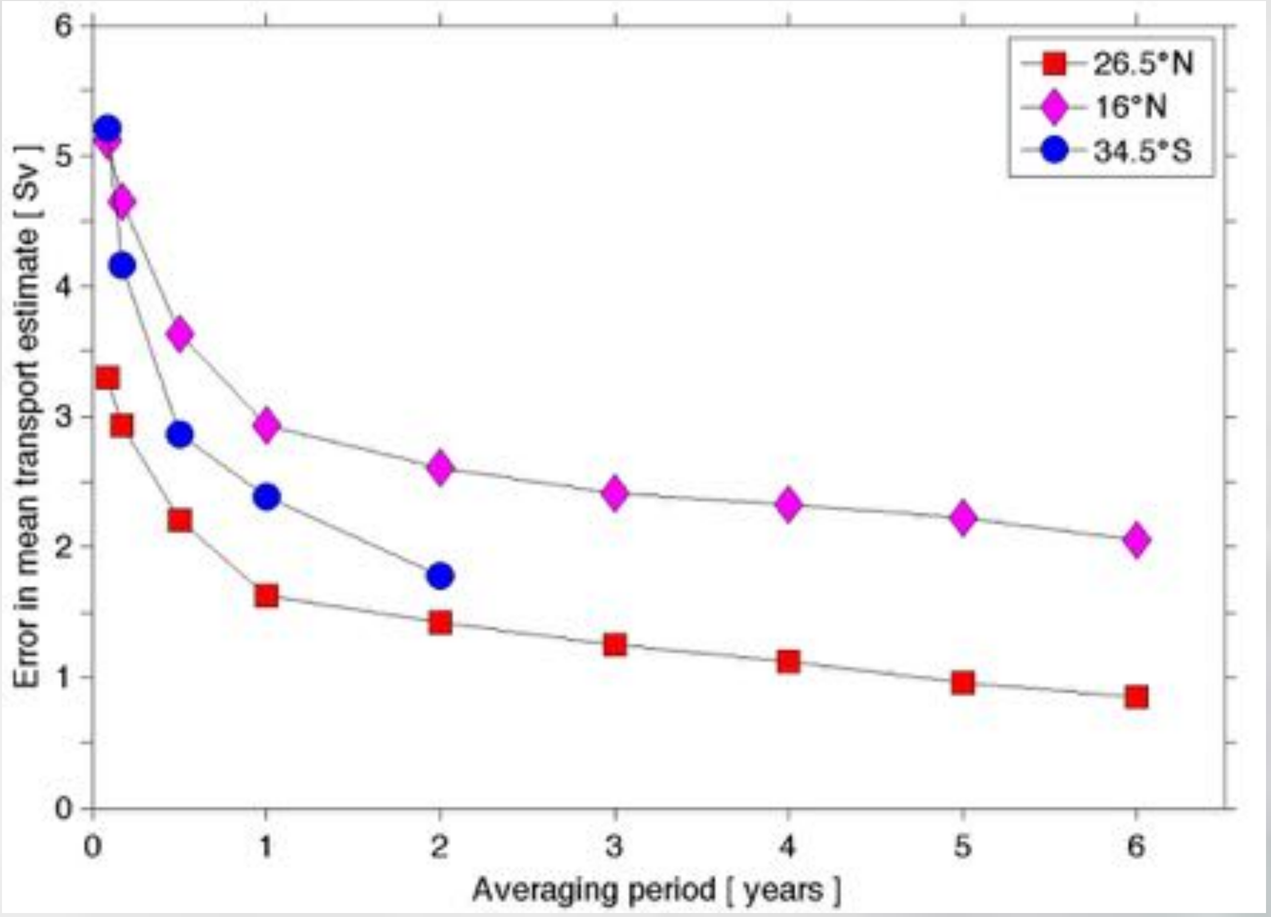
For example, different wind products are being used for the calculating the Ekman transport contributions for different arrays, and so we will be seeing differences based on this.

At first glace, the differences appear to be quite small at 34.5°S (top right), particularly the time-mean and for variability at time scales longer than 30 days (lower panel).



Consider, however, that the standard deviation of the differences (1.8 Sv at 34.5°S) is more than half of the estimated daily accuracy of the MOC estimates at 26.5°N (3 Sv; e.g. Kanzow et al. 2007), and the ~0.5 Sv differences after 30-day low-pass filtering are a significant fraction of the year-to-year changes and/or trends that have been estimated from the time series. So this does need to be considered…

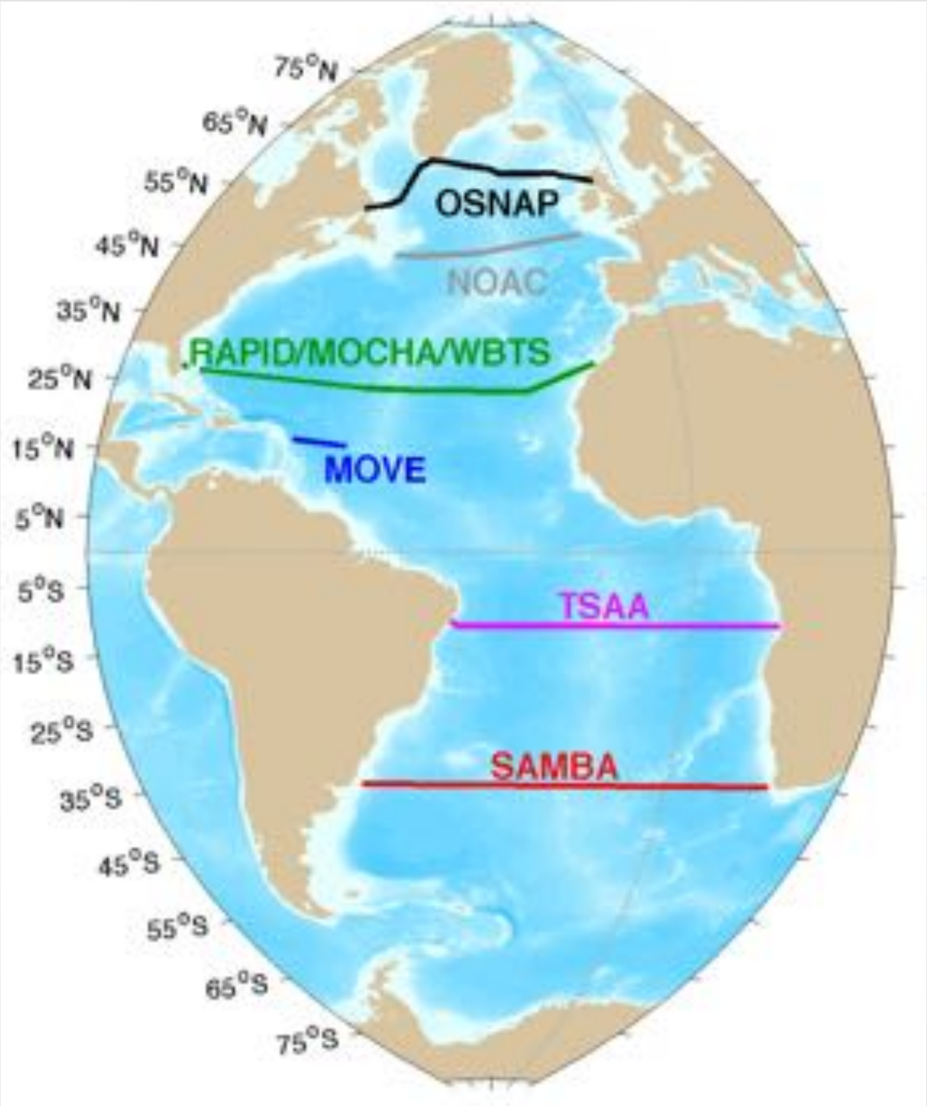
Meridional Overturning Circulation (MOC) − caveats regarding comparisons



Probably this is obvious − but we also have to be careful comparing MOC averages computed over different periods as we compare the results from the different latitudes.

Assuming our longer MOC records have captured the breadth of the variability amplitudes and time scales exhibited at those latitudes, which is a rather questionable assumption particularly for the shorter record such as the SAMBA record at 34.5°S, a simple Monte Carlo-style calculation suggests averages over short time periods may be quite different from the ‘long-term’ mean. (See 1-sigma error bars plotted above.)

Results from some of the MOC arrays: OSNAP & RAPID-MOC/MOCHA/WBTS



Now I will present some recent results from the observing system, except for the following:

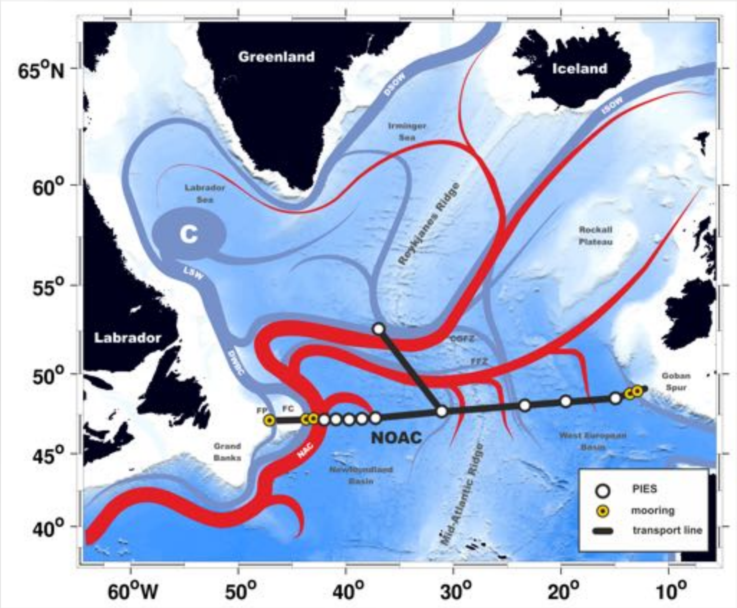
OSNAP

Results in the next talk by Feili Li

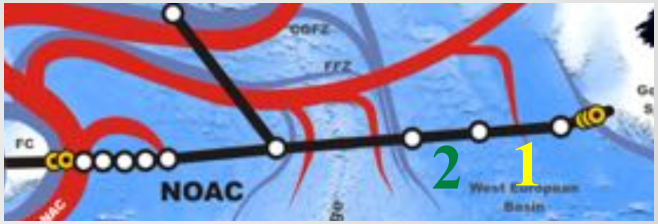
RAPID-MOC/MOCHA/WBTS

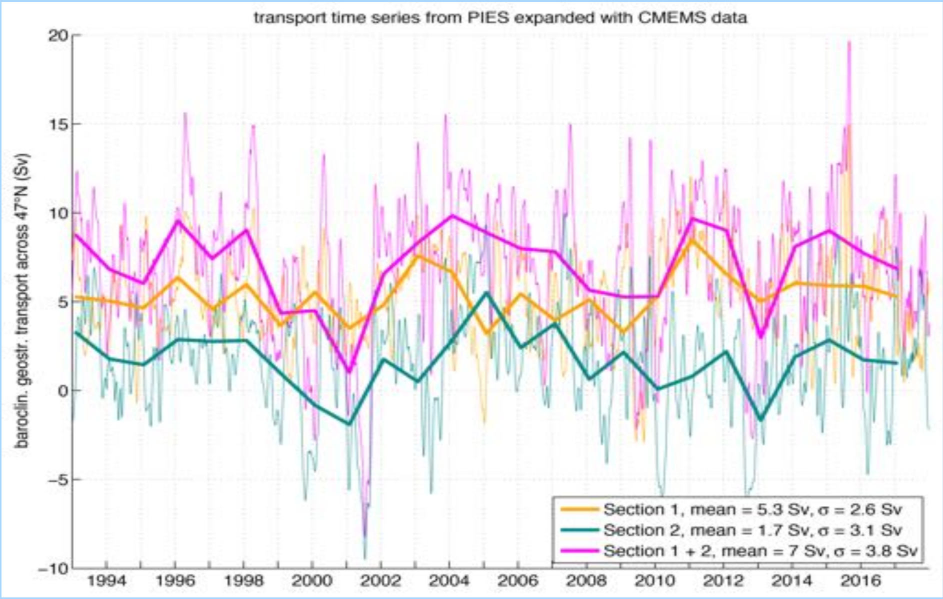
Results in later talks by David Smeed and Elaine McDonagh

Results from some of the MOC arrays: the North Atlantic Changes (NOAC) array at 47°N

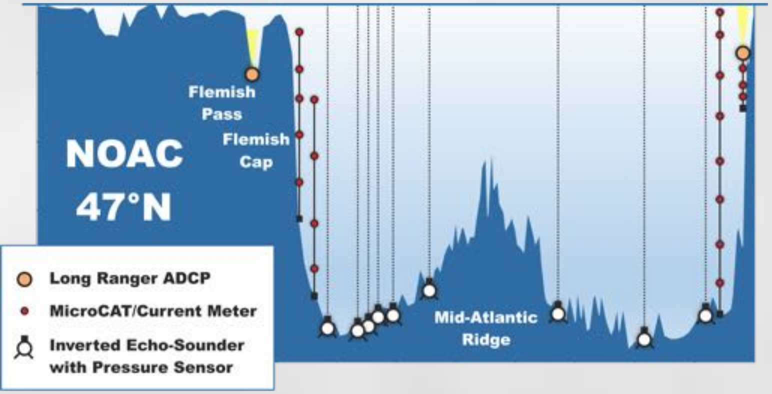


The NOAC array: Univ. Bremen and BSH, Germany
47°N west: June 2009-2020 / 47°N east: April 2016-2020





Hannah Nowitzki, PhD student Univ. Bremen

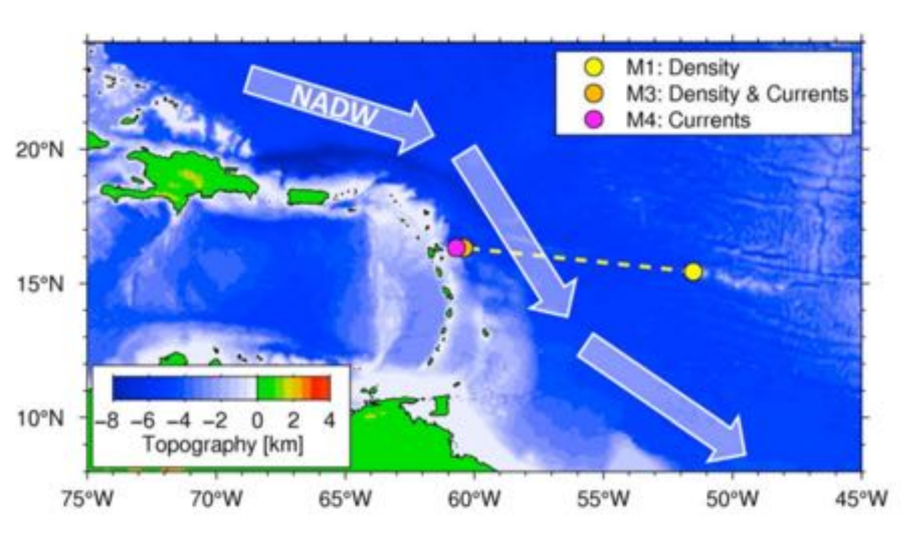


Western basin manuscript (Roessler, Mertens et al.) in prep
Eastern basin manuscript (Nowitzki et al.) in prep

MOC estimate at 47°N will be available in 2019

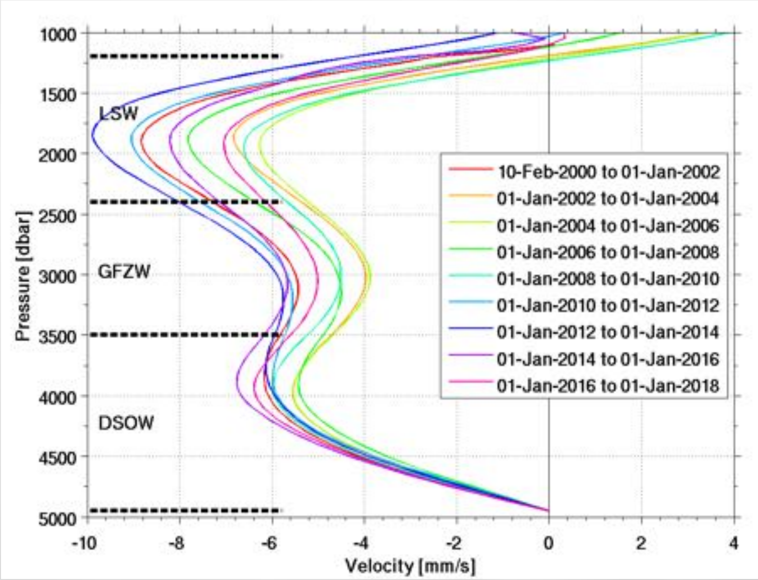
Images/info courtesy Monika Rhein

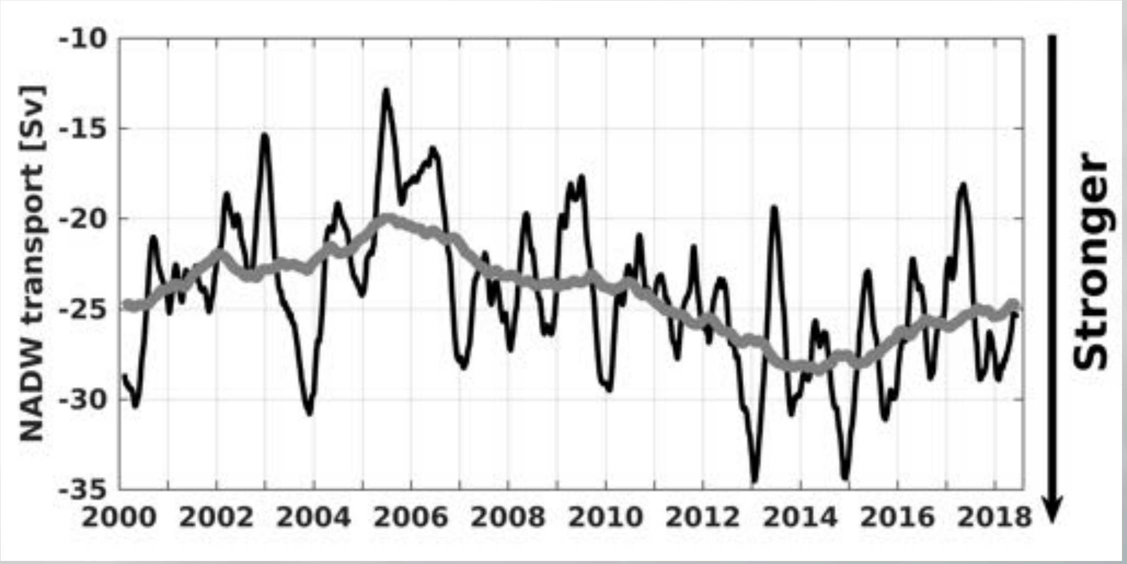
Results from some of the MOC arrays: the Meridional Overturning Variability Experiment (MOVE) at 16°N



- Southward NADW transport in Western Atlantic
- Boundary plus "internal" component (ref. level 4950 dbar)
- (Multi)Decadal variability evident in transport time series

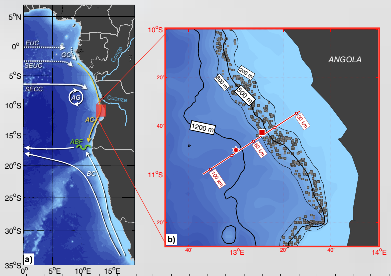
More details: Lankhorst et al. poster



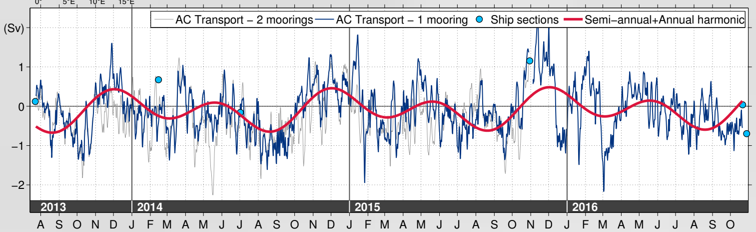


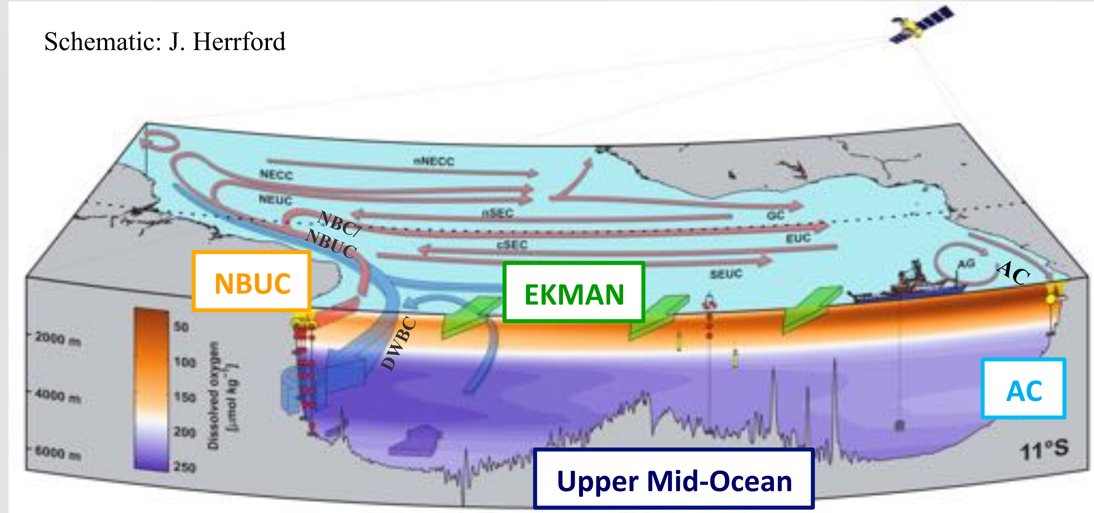
Images modified/updated from Send et al. 2011
Slide materials courtesy Jannes Koelling & Matthias Lankhorst

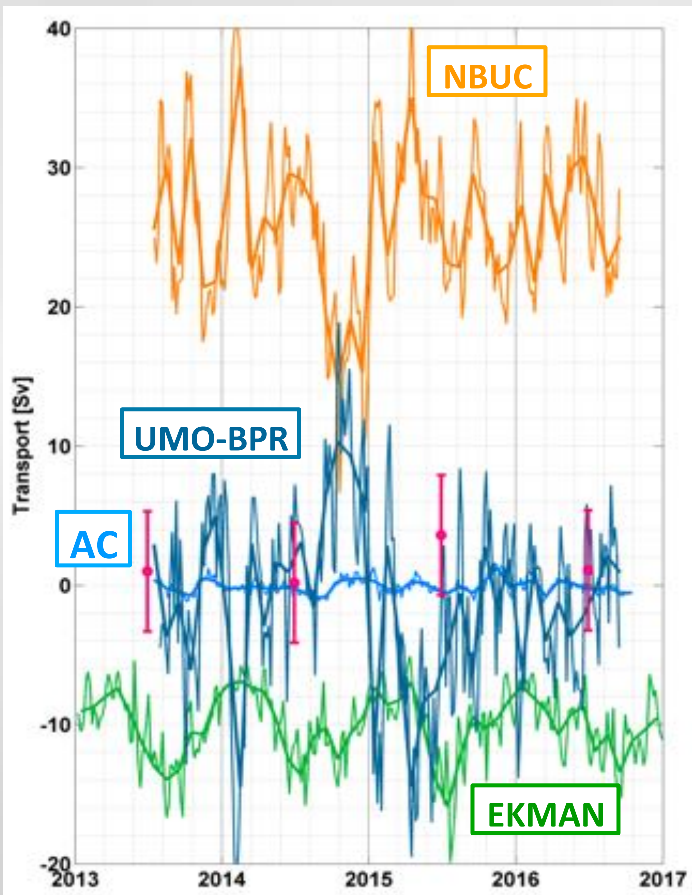
Results from some of the MOC arrays: the Tropical South Atlantic Array (TSAA) at 11°S



Angola Current mean = -0.11± 0.04 Sv







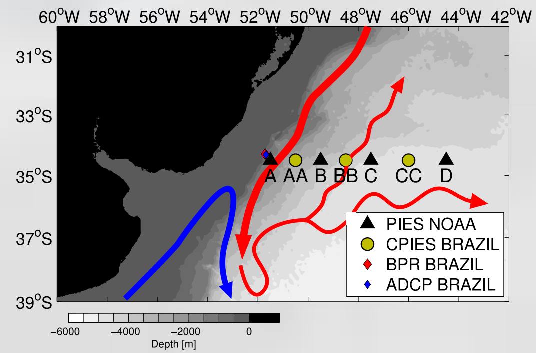
All observed AMOC contributions for 2013-2016:

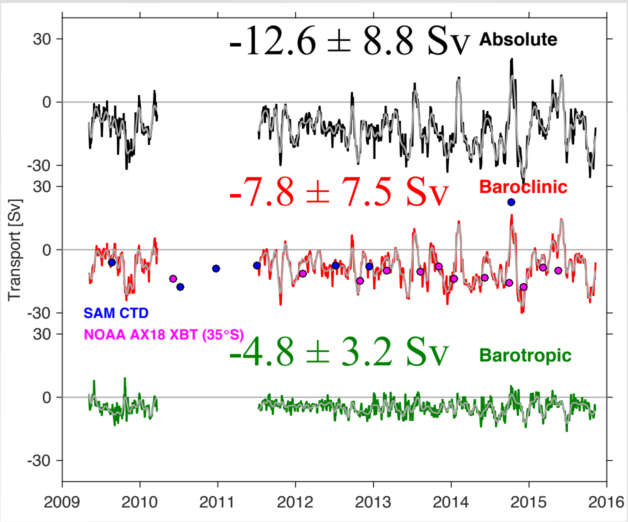
$$T_{AMOC}(t) = T_{WBC}(t) + T_{EB}(t) + T_{EK}(t) + T_{UMO}(t)$$

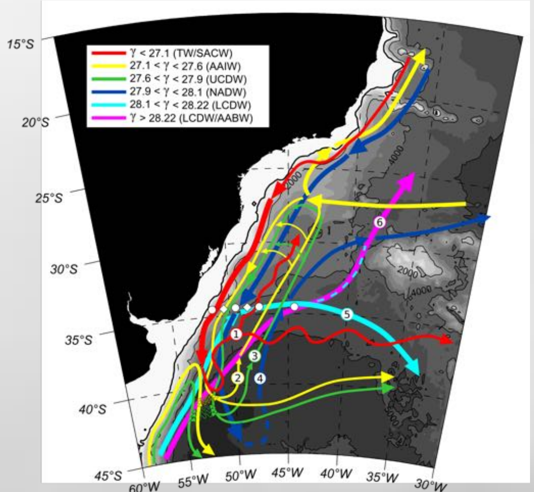
+ 25.8 Sv – 0.1 Sv – 10.1 Sv + 0.6 Sv

More updated results "coming soon" in PhD dissertations from Josefine Herrford and Robert Kopte

Slide materials: Rebecca Hummels





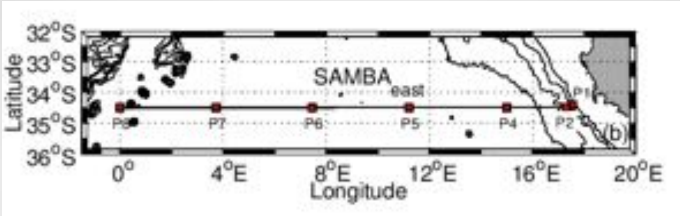


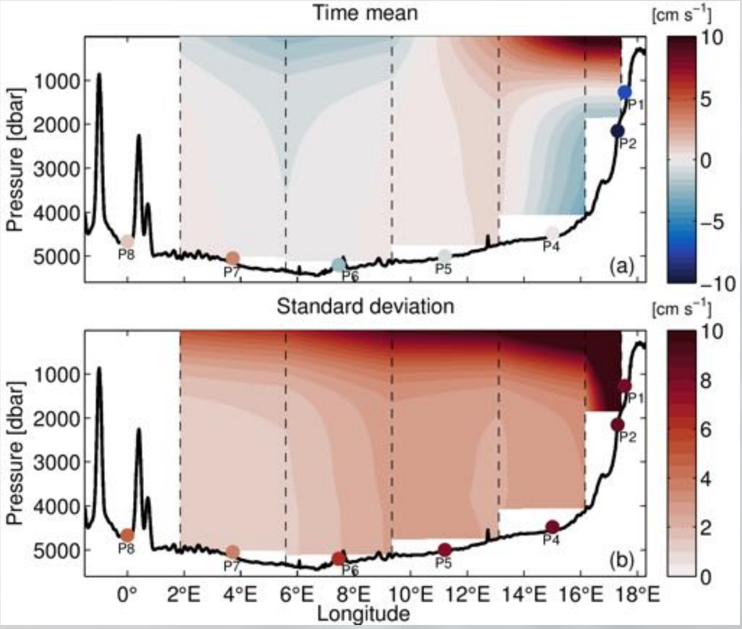
Images from Chidichimo et al. (in prep) and Valla et al. (2018)

Results from some of the MOC arrays: the South Atlantic MOC Basin-wide Array (SAMBA) at 34.5°S

Main Results:

- Flows at both boundaries are exhibiting strong baroclinic and barotropic variations
- Water mass signals at both boundaries indicate the presence of recently ventilated NADW, confirming two pathways for the lower limb of the MOC at 34.5°S.

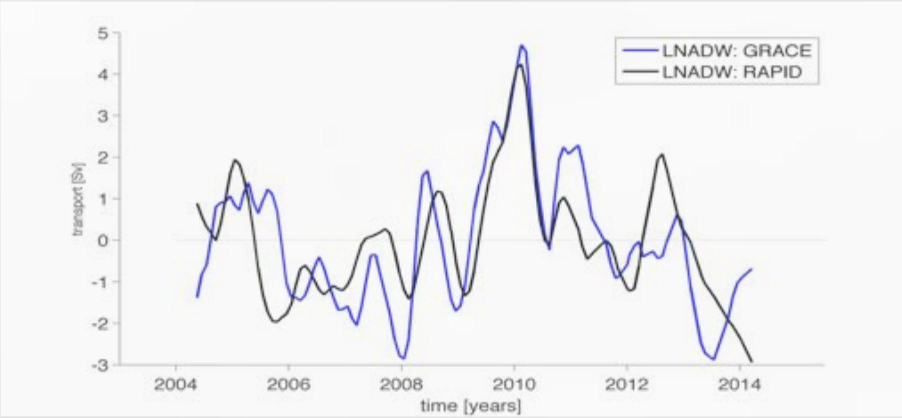




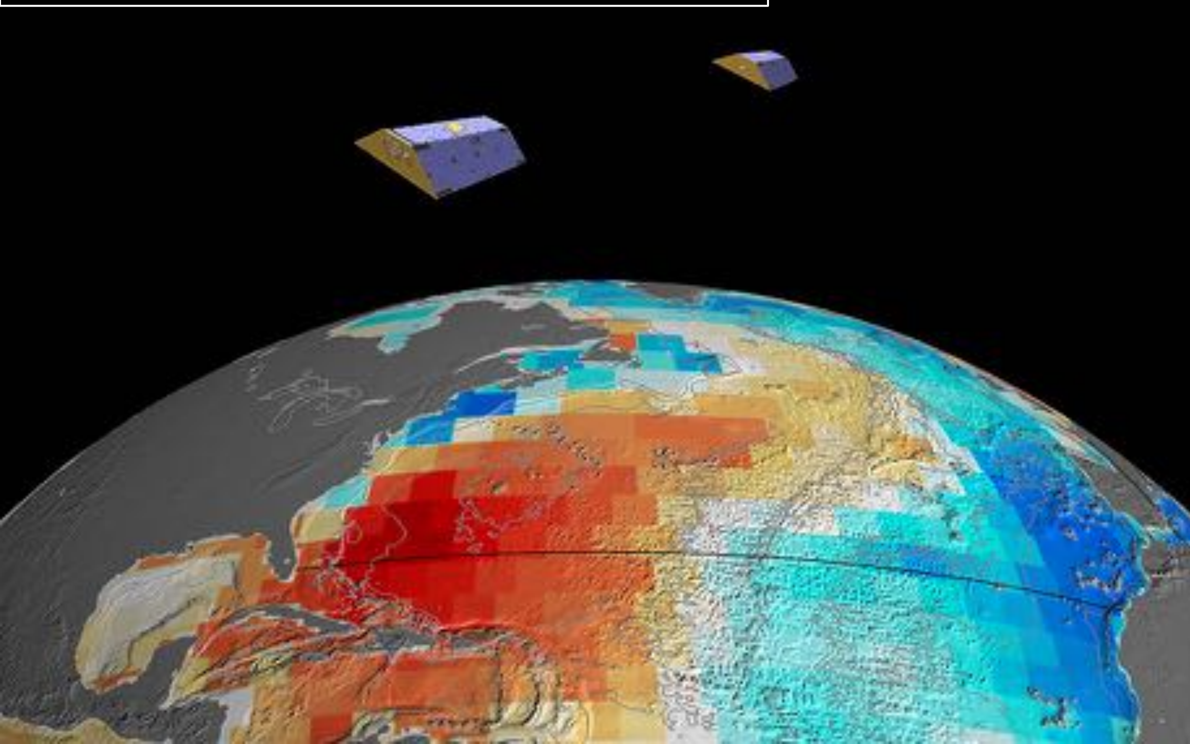
Images from Kersale et al. (in prep)

- We now have ~6 years of daily MOC estimates from the SAMBA array – please see our posters for more details.

Examples of MOC estimates from other systems: Detection of MOC at 26.5°N with GRACE



Landerer, Wiese, Bentel, Boening, Watkins (2015), North Atlantic meridional overturning circulation variations from GRACE ocean bottom pressure anomalies, ***GRL.***



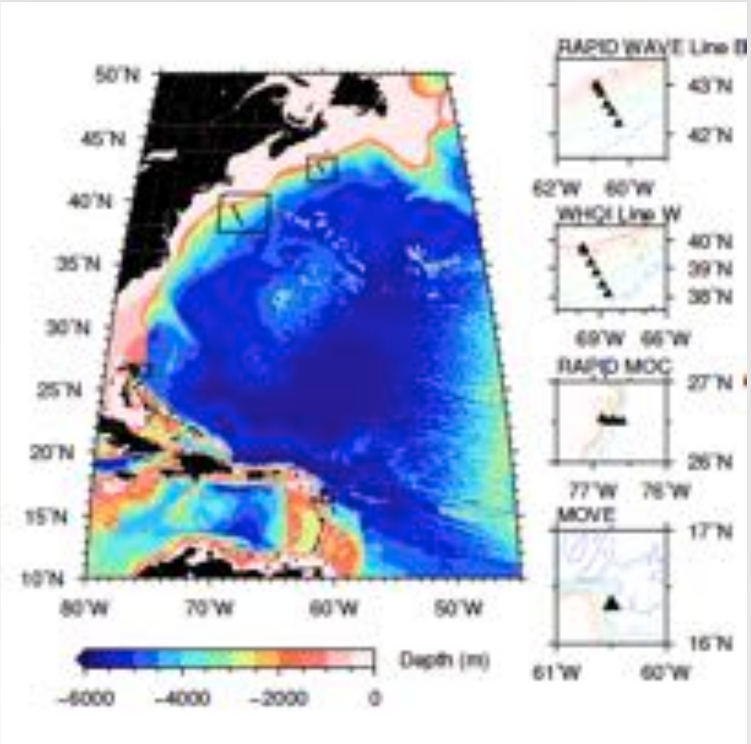
Main Results:

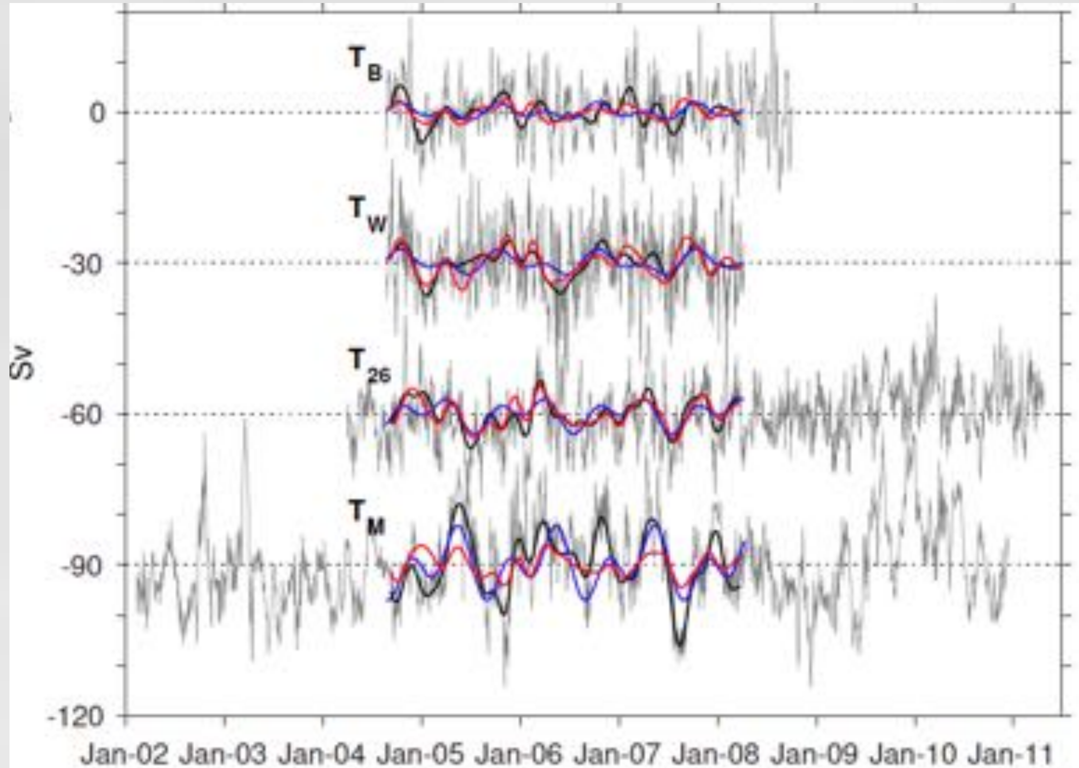
- New JPL GRACE mascon solution allows detection of basin-wide ocean volume transports
- Observed prominent AMOC anomaly in winter of 2009/2010
- Will be used to address open science questions about AMOC dynamics
- Good agreement with in-situ observations at 26.5°N suggest new applications of satellite gravimetry for long-term, global ocean circulation & climate monitoring

(Slide courtesy Felix Landerer)

Jet Propulsion Laboratory
California Institute of Technology

<u>Examples of MOC-related signals from other systems: Coherence of DWBC flows</u>
41°N, 39°N, 26.5°N, 16°N

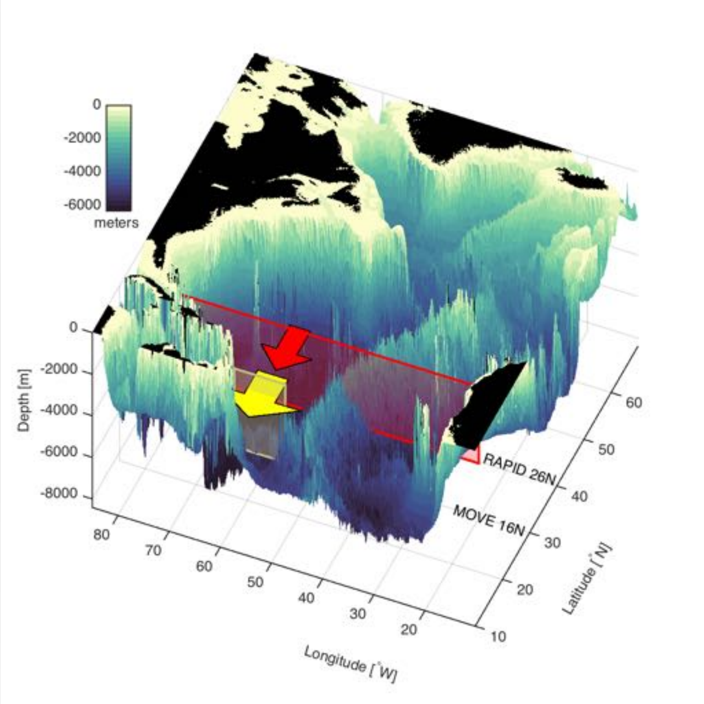




Results from Elipot et al. (2017)

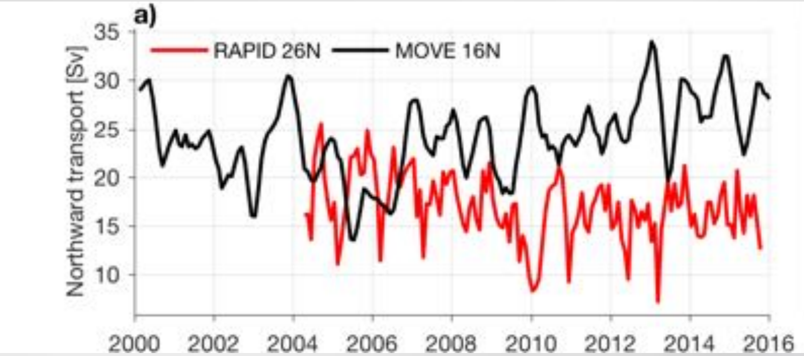
Four 3.6-year time series of deep transport (1000-4000 m) along the western boundary used to study the lower limb of the MOC – EOF analysis demonstrating that more than 50% of the variance in the 3-month low-pass filtered variance can be explained by wind forcing (seasonal + NAO).

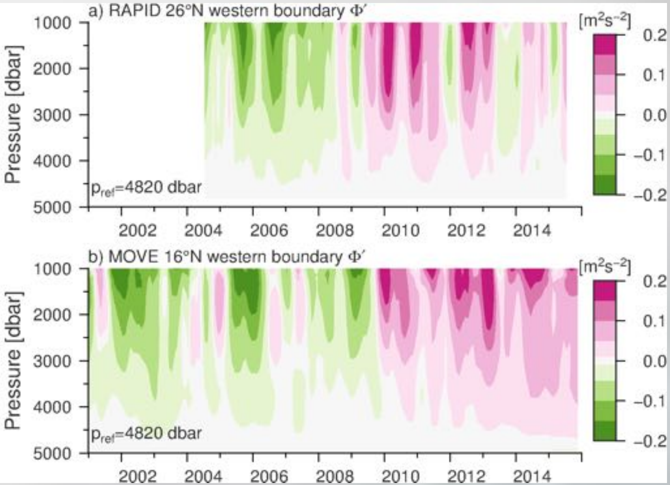
(Information courtesy Shane Elipot)

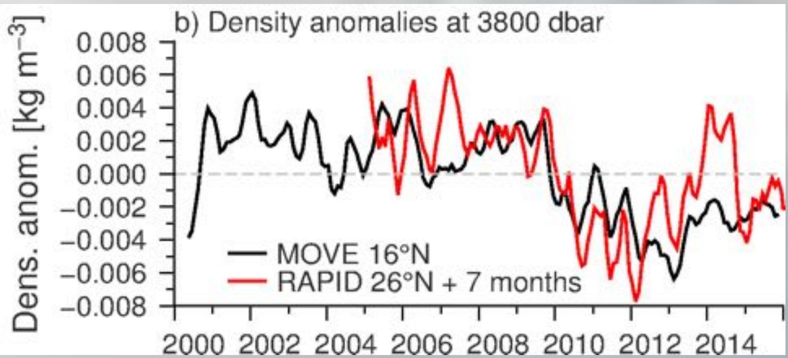


Comparison of the MOC at 16°N and 26.5°N

Decadal variability





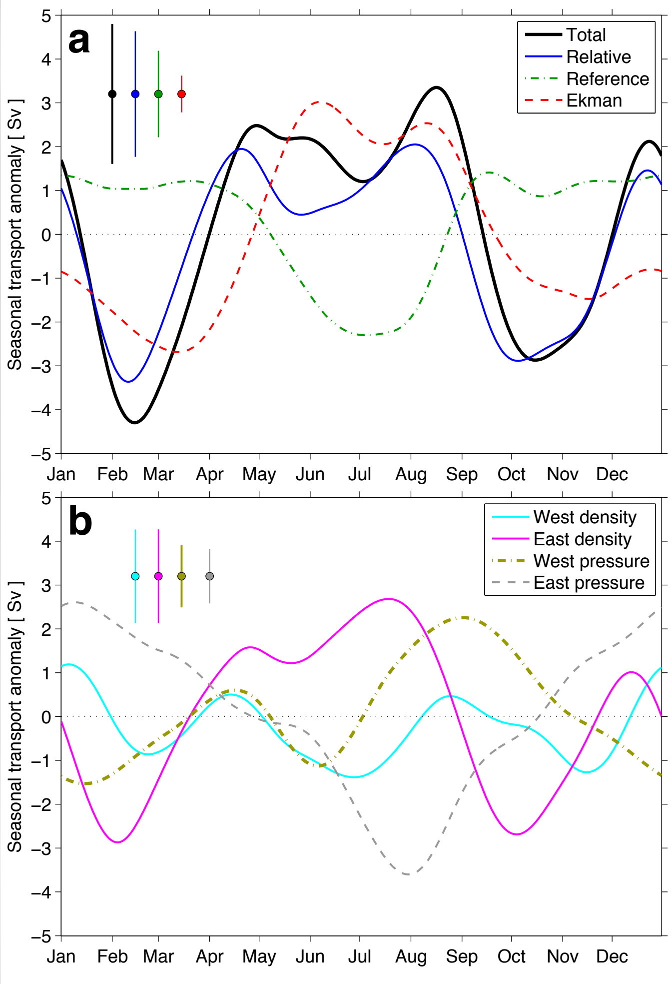


Frajka-Williams et al. (2018) has compared the MOC at 16°N and 26.5°N and found:

- Quasi-decadal trends of roughly similar magnitude, but opposite sign (at above right)
- Highly correlated baroclinic (density) variations at the western boundary (at right), with a ~7 month lag (bottom right)
- Indications that the decadal trend difference is associated with the zero-net-mass correction/ residual (see Lankhorst et al. poster for more)

Comparison of the MOC at 34.5°S and 26.5°N

Seasonal variability

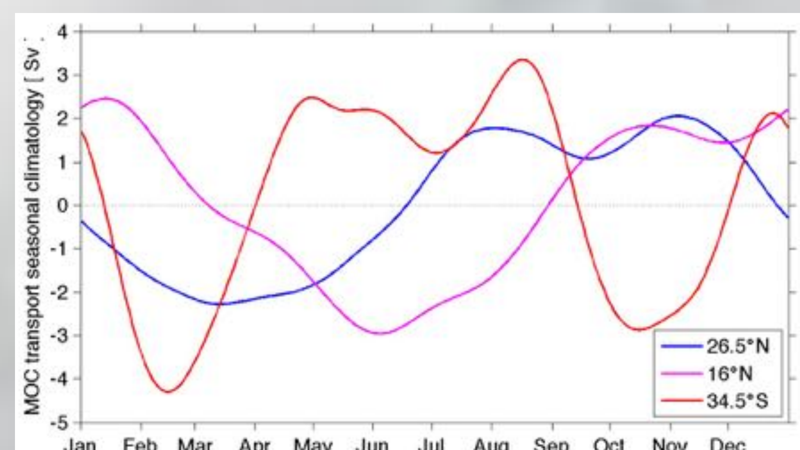


Meinen et al. (2018) has produced a daily MOC seasonal climatology at 34.5°S and found:

- The total MOC seasonal cycle has a more dominant semi-annual time scale to it
- The Ekman and barotropic (reference, i.e. bottom pressure) seasonal cycles are dominated by the annual time scale and are roughly 180° out of phase with each other
- Baroclinic seasonality is driven more by changes in the east, but barotropic seasonality is impacted by changes at both boundaries (see Meinen et al. poster for more detail)

Comparing seasonal variability at 34.5°S, 16°N & 26.5°N:

- Seasonal variability is stronger at 34.5°S
- At 26.5°N & 16°N there is little semi-annual signal
- Both west and east sides of the basin impact the seasonal variability at 34.5°S, while at 26.5°N only the east side variability seems to be important



Comparison of the MOC at 34.5°S and 26.5°N: Interannual variability

Comparing the annual mean MOC at 34.5°S and 26.5°N illustrates:

- Peak-to-peak range of annual averages is larger at 34.5°S (~8 Sv vs. ~5 Sv)
- Only one major shift seen at 26.5°N (2008 to 2009); two major shifts seen at 34.5°S (decrease 2009 to 2010 & increase 2014 to 2015; note these years are not instrument changeover years)
- Most of the smaller year-to-year variations are not statistically significant based on the estimated standard error of the mean at 34.5°S
- Interannual is driven by Ekman and density signals in west at 26.5°N (e.g. Zhao and Johns 2014; Frajka-Williams 2015; McCarthy et al. 2015), but both sides matter at 34.5°S (Meinen et al. 2018).

26.5°N: Calendar Year MOC averages

2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	*2017*
19.1 Sv	19.3 Sv	19.1 Sv	18.1 Sv	17.6 Sv	14.6 Sv	15.0 Sv	16.8 Sv	15.1 Sv	16.3 Sv	16.0 Sv	17.2 Sv	17.0 Sv	*16.4 Sv*

Items in italics indicate years with less than 9 months for averaging (2004 & 2017). Calculated from public time series.

34.5°S: Calendar Year MOC averages

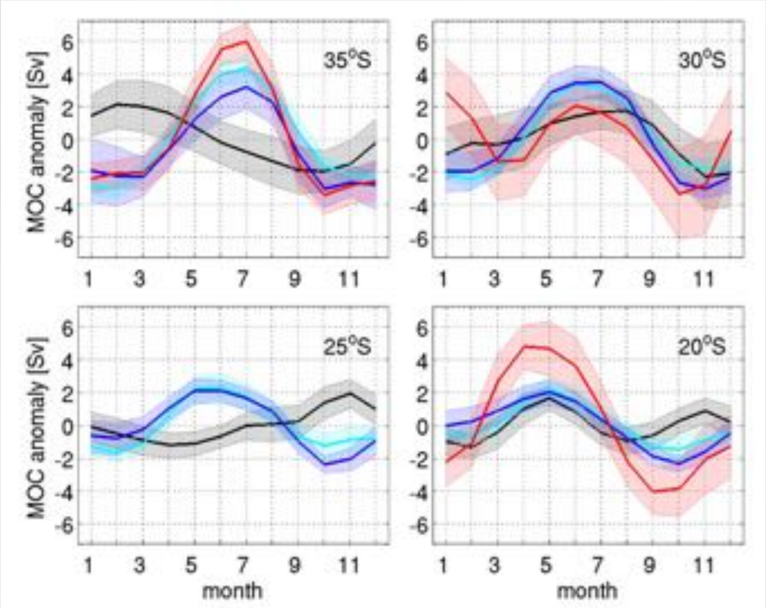
	2009	2010	2013	2014	2015	2016	2017	SEM
Total MOC	**4.6 Sv**	**−1.8 Sv**	***−3.4 Sv***	**−3.8 Sv**	**3.2 Sv**	**0.3 Sv**	***−1.9 Sv***	**1.7 Sv**
Ekman contribution	0.7 Sv	−0.6 Sv	*−1.2 Sv*	−0.0 Sv	−0.1 Sv	0.5 Sv	*−2.3 Sv*	0.9 Sv
Relative contribution	4.2 Sv	0.3 Sv	*−3.5 Sv*	−4.2 Sv	0.9 Sv	−0.1 Sv	*−2.5 Sv*	1.5 Sv
Reference contribution	−0.3 Sv	−1.3 Sv	*1.0 Sv*	0.4 Sv	2.1 Sv	−0.4 Sv	*2.6 Sv*	1.0 Sv
West density contribution	1.8 Sv	−1.3 Sv	*−0.4 Sv*	−1.3 Sv	1.8 Sv	−1.4 Sv	*−2.3 Sv*	1.1 Sv
East density contribution	2.5 Sv	1.6 Sv	*−3.2 Sv*	−2.9 Sv	−0.9 Sv	1.3 Sv	*−0.2 Sv*	1.2 Sv
West pressure contribution	0.4 Sv	−0.3 Sv	*0.4 Sv*	0.0 Sv	0.9 Sv	−0.3 Sv	*0.2 Sv*	0.9 Sv
East pressure contribution	−0.8 Sv	−1.1 Sv	*0.5 Sv*	0.2 Sv	1.0 Sv	−0.1 Sv	*2.2 Sv*	0.8 Sv

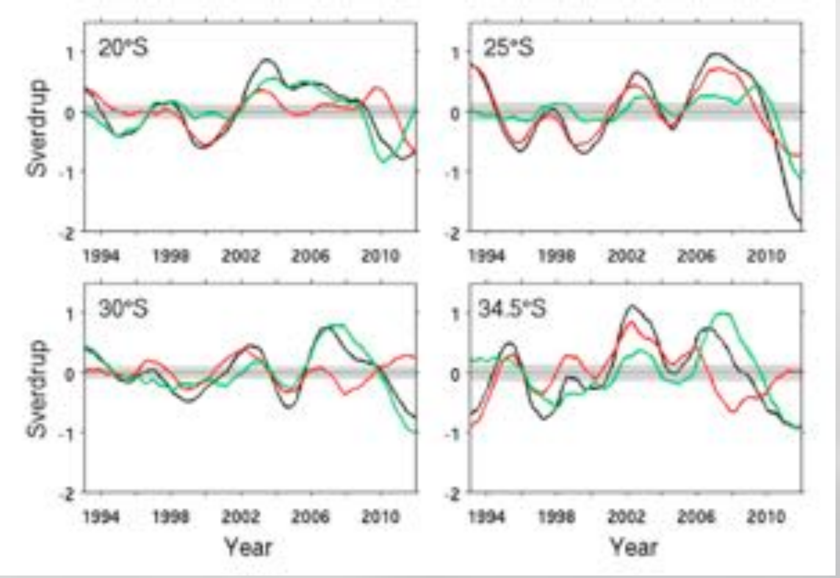
Items in italics indicate years with less than 9 months for averaging (2013 & 2017). From Meinen et al. (2018)

Other MOC systems are also being used to look at latitudinal coherences and differences

Majumder et al. (2016) used a blend of Argo and satellite altimeter observations to estimate the MOC at several latitudes within the South Atlantic:

- Amplitudes of the observed MOC seasonality (black lines) appear to decrease closer to the equator.
- Model agreement with the Argo-altimetry estimates varies at different latitudes and for different models, but in general is marginal. (Blue-NCEP/GODAS; Cyan-SODA; Red-HYCOM)
- Argo-altimetry seasonality at 35°S is quite different from the moored estimates at 34.5°S.





Dong et al. (2015) used a blend of Argo/CTD/XBT and satellite altimeter observations to estimate the MOC at several latitudes within the South Atlantic:

- Amplitudes of the observed MOC interannual variability (black lines) have little latitudinal dependence.
- There is little coherence at interannual time scales from neighboring latitudes.
- Hydrography-altimetry interannual variability at 34.5°S is much weaker than what is estimated from the moored estimates at 34.5°S.

Conclusions

- After 10+ years of hard work by the international community, the MOC observing system is providing outstanding results and it is still growing. The next 5+ years should yield a wealth of data for study of the mechanisms and pathways of the MOC, especially with these new arrays (OSNAP, NOAC, TSAA) and the new techniques folks are developing (satellites, proxy methods, etc.).
- The differences in how the MOC is being determined at different latitudes makes comparison complex, and these nuances must be considered in the interpretation. (Complicating analysis of long-term trends, e.g. comparison of 16°N and 26.5°N).
- The MOC seasonal cycle appears to be both stronger (larger amplitude) and more complex (semi-annual & annual) at 34.5°S than at 26.5°N. Comparisons with other latitudes should be available over the next few years as some of the newer arrays get enough years.
- Interannual MOC variability also appears to be stronger (larger amplitude) and more complicated at 34.5°S than at 26.5°N, with variations at both boundaries being important at 34.5°S but mostly only the west side impacting this time scale at 26.5°N. Again, comparisons with the other latitudes will be coming soon.

These are hopefully just a few of the exciting results that are coming from the MOC observing system. The next four days of talks should elucidate many more…

Questions?