AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL063220

Key Points:
- Western boundary dynamic height governs interannual variability of transports
- Sea level anomalies in the west anticorrelate transbasin transports at 26°N
- The MOC 1993–2014 weakened (-1 Sv) due to a weakening of the Florida Current

Correspondence to:
E. Frajka-Williams,
E.Frajka-Williams@noc.soton.ac.uk

Citation:
Frajka-Williams, E. (2015), Estimating the Atlantic overturning at 26°N using satellite altimetry and cable measurements, *Geophys. Res. Lett.*, *42*, 3458–3464, doi:10.1002/2015GL063220.

Received 22 JAN 2015
Accepted 2 APR 2015
Accepted article online 7 APR 2015
Published online 11 May 2015

Estimating the Atlantic overturning at 26°N using satellite altimetry and cable measurements

E. Frajka-Williams[1]

[1]Ocean and Earth Sciences, University of Southampton, Southampton, UK

Abstract Climate simulations predict a slowing of the Atlantic meridional overturning circulation (MOC), a key oceanic component of the climate system, while continuous observations of the MOC from boundary arrays demonstrate substantial variability on weekly to interannual time scales. These arrays are necessarily limited to individual latitudes. A potential proxy for the MOC covering longer time scales and larger spatial scales is desirable. Here we use sea surface height data from satellites to estimate the interannual variability of transbasin ocean transports at 26°N. Combining this estimate with surface Ekman transport and cable measurements of the Florida Current, we construct a time series of the MOC from 1993 to 2014. This satellite-based estimate recovers over 90% of the interannual variability of the MOC measured by the RAPID 26°N array. This analysis complements in situ observational efforts to measure the MOC at multiple latitudes and opens the door to a broader spatial understanding of the Atlantic circulation variability.

1. Introduction

The Atlantic meridional overturning circulation (MOC) is characterized by warm waters flowing northward at the surface and cool waters flowing southward at depth. Due to the temperature difference between these transports, heat is fluxed northward, with the MOC responsible for roughly 25% of the northward heat transport at 26°N [*Hall and Bryden*, 1982]. In a warming climate, numerical simulations suggest that the MOC will slow in the near future, with implications for regional climate changes across Europe and beyond [*Meehl et al.*, 2007]. Traditionally thought of as a slowly varying circulation, the overturning has been estimated from hydrographic sections. Using five sections at 26°N, the circulation was found to have slowed by 30% over the period 1957–2004 [*Bryden et al.*, 2005].

Since 2004, the RAPID/MOCHA (Rapid Climate Change/Meridional Overturning Circulation and Heatflux Array) observational program at 26°N (hereafter, RAPID 26°N) has been delivering depth-resolved estimates of the transbasin volume and heat transports across the North Atlantic [*Johns et al.*, 2011; *McCarthy et al.*, 2015]. These continuous observations at 26°N have been transformative in our understanding of the meridional overturning circulation, identifying, for example, that the 30% reduction calculated from hydrographic sections over 1957–2004 [*Bryden et al.*, 2005] was not significant, due to large variability on subannual [*Cunningham et al.*, 2007] and seasonal time scales [*Kanzow et al.*, 2010]. More recently, the RAPID observations have identified a reducing trend of the MOC, at a rate of −0.5 sverdrups per year (Sv/yr) [*Smeed et al.*, 2014]. However, numerical simulations call into question the relevance of this slowing amidst substantial lower frequency variability [*Roberts et al.*, 2014]. Due to the present length of records from RAPID (10 years), it is not yet possible to directly assess the lower frequency variability of ocean transports.

While RAPID 26°N provides the most comprehensive measurements of the MOC, it is necessarily limited in space (to 26°N) and time (since 2004). Numerical studies have suggested that sea level anomalies (SLA) may be a useful proxy for oceanic transports. *Bingham and Hughes* [2009] found that SLA along the East Coast of North America are a good proxy for the MOC between 40 and 50°N. *Willis* [2010] used altimetry along with Argo float profiles to calculate transport at 41°N, based on model simulations indicating that the methodology only works around 41°N. At 26°N, transbasin transports were found to covary with the differences in SLA between the west and east of the basin [*Hirschi et al.*, 2007]. However, the correlation was degraded somewhat in observations by the absence of steric height measurements (related to density) in the top 200 m [*Ivchenko et al.*, 2011]. SLA and bottom pressure can be related to depth-dependent (baroclinic) and depth-independent (barotropic) transports in the ocean. Model studies have found that SLA is mirrored by bottom pressure fluctuations on shorter time scales, at higher latitudes and over shallower regions; on longer time scales, at lower latitudes, and over deeper regions, SLA is associated with steric (or dynamic) height anomalies [*Vinogradova et al.*, 2007].

In the present paper, I revisit the relationship between transport and SLA, leveraging the expectation that interannual variability of baroclinic transports should be related to SLA. I determine a statistical relationship between the 10 year record of transports from RAPID at 26°N and SLA. Following this, I derive an estimate for the interannual variability of the MOC using satellite SLA for the period 1993–2014.

2. Data

2.1. Moored Observations

The RAPID 26°N array has been making comprehensive measurements of transbasin transports since April 2004, with the present time series available through March 2014. The observational approach is to estimate transbasin meridional transport between the Bahamas and Canary Islands and to combine it with flow through the Florida Straits, estimated from a submarine telephone cable [*Meinen et al.*, 2010] and meridional Ekman transport from reanalysis winds.

Meridional velocities in the ocean are proportional to zonal pressure gradients through geostrophy. Meridional transport, our measure of ocean circulation, is the integral of meridional velocity across a zonal section. From the RAPID methodology, the geostrophic transport per unit depth between the Bahamas and Canary Islands is derived from the thermal wind relation as

$$T_{\mathrm{int}}(p) = \frac{\Phi_{\mathrm{east}}(p) - \Phi_{\mathrm{west}}(p)}{f} \tag{1}$$

where f is the Coriolis parameter and Φ_{east} and Φ_{west} are the dynamic height anomalies relative to zero at 4820 dbar at the east and west of the Atlantic, respectively. (See full details of the calculation in *McCarthy et al.* [2015].) Dynamic height is estimated from measured density profiles as

$$\Phi(p) = \frac{1}{\rho_0}\int_{4820}^{p} \delta(p')\,\mathrm{d}p',$$

where ρ_0 is a constant reference density and δ, related to $1/\rho$, the specific volume anomaly.

The interior geostrophic transport per unit depth is combined with the wedge transports (direct current meter measurements east of the Bahamas) and a compensation term. The compensation term is calculated as the residual required to balance the net transport across the section and was found to covary with bottom pressure observations at 26°N [*Kanzow et al.*, 2007]. Together, these three transports form the full mid-ocean meridional transport between the Bahamas and Canary Islands. The MOC across 26°N is then estimated as the net northward transport above the depth of maximum overturning (roughly ∼1100 m), constructed as the sum of three components: (1) the mid-ocean transport, (2) the meridional Ekman transport at the surface, and (3) the Florida Current transport. The portion of mid-ocean transport above the depth of maximum overturning circulation is called the upper mid-ocean (UMO) transport and is the focus of the comparisons here between SLA and transports. UMO transport has units of sverdrups (1 Sv $= 1 \times 10^6$ kg m^{-3}) and represents the transbasin meridional transport in the top roughly 1100 m but excluding the surface Ekman transport.

The published RAPID time series have been 10 day low-pass filtered with a fifth-order Butterworth filter. For this study, time series are further bin averaged onto a monthly time grid to match SLA. A seasonal climatology is removed, then residual anomalies are smoothed with a 1.5 year Tukey filter. This processing reduces the strong seasonal cycle as well as other subannual variations.

2.2. Sea Level Anomalies

The monthly 1/4° delayed time, mapped sea level anomaly (DT-MSLA) from AVISO (Archiving, Validating and Interpretation of Satellite Oceanographic Data) was used for 1993–2014. At full resolution, eddies contribute to the variability of SLA and, comparing SLA to transports at 26°N, were found to govern the subannual variability of the Antilles Current, a western boundary current east of the Bahamas [*Frajka-Williams et al.*, 2013]. In order to focus on the large-scale circulation, the influence of eddies on SLA is reduced by spatially smoothing SLA with a 5° × 10° moving window then subsampling onto a 1° grid. The seasonal climatology of SLA at each point is removed, then residuals are smoothed with a 1.5 year Tukey filter.

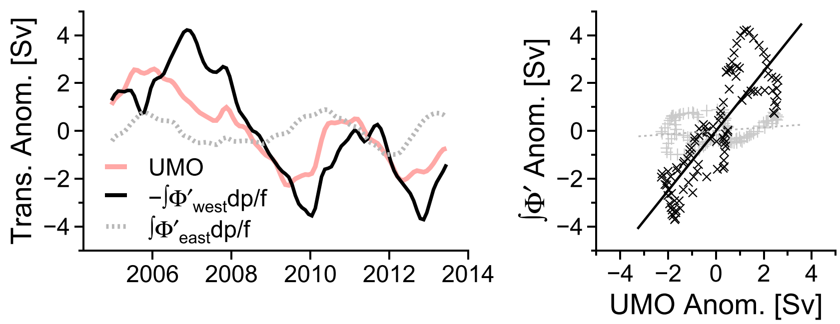

Figure 1. (left) Upper mid-ocean transport anomalies (pink) and transport anomalies estimated from dynamic height anomalies ($\int_{1100}^{0} \Phi'(p)\,dp/f$) at the western (black) or eastern (grey dashed) boundary. (right) Scatterplot between UMO transport and dynamic height anomalies, scaled and integrated, with best fit regression lines overlaid. The regression between UMO and dynamic height at the west is significant, $r = 0.8$, but not with the east, $r = 0.2$.

SLA will be compared to transbasin geostrophic transport at 26°N. SLA (η) and steric height anomalies (η_{st}) differ by bottom pressure anomalies (p_b) as

$$\eta = \eta_{st} + \frac{p_b}{g\rho_0}, \tag{2}$$

where steric height is dynamic height at the surface, scaled by gravitational acceleration g ($\eta_{st} = \Phi(0)/g$). From an ocean state estimate, interannual variability of SLA in the subtropical North Atlantic was found to be governed by dynamic height anomalies in the upper ocean [*Piecuch and Ponte*, 2011], while satellite-derived estimates found SLA and bottom pressure to be mostly uncorrelated on interannual time scales [*Piecuch et al.*, 2013]. Together, these suggest that SLA will be related to interannual variations in transport.

In computing statistical significance of correlations, the number of degrees of freedom for each time series is determined using the integral time scale of decorrelation. For the filtered UMO time series, there are 8 degrees of freedom. For SLA, number of degrees of freedom is determined at each grid point.

3. Results

3.1. Interannual Transport Variability

At 26°N, UMO transport variations contributed to a dip in the MOC in 2009/2010 [*McCarthy et al.*, 2012] as well as its reducing trend over 2004–2012 [*Smeed et al.*, 2014]. While the UMO is composed of three transports (interior geostrophic, wedge, and compensation), its variability on interannual time scales is primarily determined by the geostrophic transports. To see this, we approximate the geostrophic contributions to transbasin transport per unit depth using (1) with dynamic height anomalies at the eastern and western boundaries only. Comparing the simplified geostrophic transports ($\int_{1100}^{0}\Phi'_{east} - \Phi'_{west}\,dp/f$) with the full UMO transport, we find a strong correlation ($r = 0.9$).

By further separating the dynamic height contributions to their respective boundaries, east ($\int_{1100}^{0}\Phi'_{east}\,dp/f$) and west ($-\int_{1100}^{0}\Phi'_{west}\,dp/f$), we can localize the origin of interannual variability to the UMO transport. On interannual time scales, the UMO transport is dominated by dynamic height anomalies at the west (Figure 1, $r = 0.83$ for west), with little contribution from density anomalies at the eastern boundary ($r = 0.2$). These western anomalies capture the 2009/2010 dip as well as the longer-term reduction of the UMO. While the amplitude of dynamic height variations is greater than UMO variations, this may result from the slightly off-shore mooring position (25 km from the Bahamas) being more susceptible to eddy noise [*Clément et al.*, 2014]. Adding the transport in the wedge (within 25 km of Bahamas) to the dynamic height transports reduces the variations at the west (not shown).

3.2. Relationship With SLA

To compare the transbasin transport with SLA, a pointwise correlation is calculated between the full UMO and SLA (Figure 2). The mapped correlations show the fingerprint of the UMO transport on SLA across the North Atlantic, with strongest anticorrelation in the western subtropical Atlantic. This inverse relationship is consistent with expectations: a positive SLA (upward movement of the sea surface) is associated

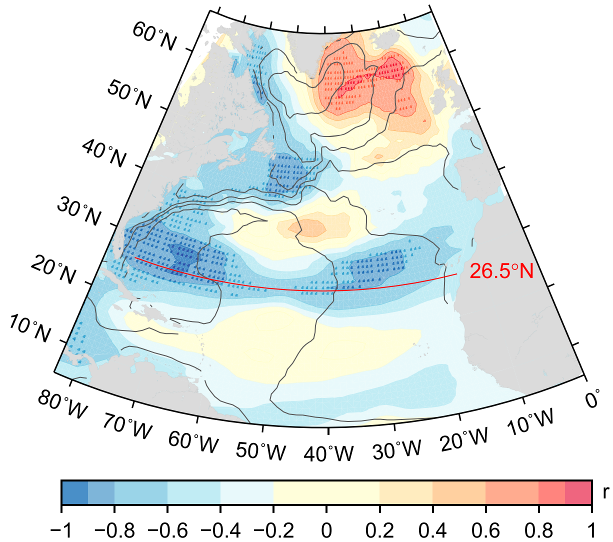

Figure 2. Correlation coefficient between SLA and upper mid-ocean transport at 26.5°N. Red indicates positive correlation, and blue negative. Stippled regions are significant at the 95% level. Mean dynamic ocean topography is overlaid with black contours (contour interval, 20 cm).

with a downward displacement of the thermocline. At 26°N, when the thermocline is depressed downward, the east-west tilt of the thermocline is intensified, and the UMO transport is enhanced southward [*Longworth et al.*, 2011; *McCarthy et al.*, 2012]. In particular, a sea level rise of 2 cm is associated with a southward intensification of the UMO by 1 Sv.

The larger spatial pattern of the correlation raises many questions. For example, the broad region of anticorrelation along the continental shelf of North America is suggestive of fast (<1 year), coherent anomalies along the western boundary. These patterns of variability will not be explored further here. Instead, we will use the time series of SLA at the center of action (30°N, 70°W) to estimate transbasin transports.

3.3. Estimating Transbasin Transports From Altimetry

The strong relationship between the UMO and SLA offers a tantalizing opportunity to estimate transbasin transports in the period prior to RAPID's installment in 2004. While meridional velocities arise from pressure differences between the east and west, because dynamic height anomalies from RAPID show little variability in the east, velocities are dominated by variations at the west. The importance of the western boundary is consistent with previous numerical studies. At 26°N, *Hirschi et al.* [2007] found that sea level anomalies in the east and west contribute differently to transport variability. From numerical simulations, *Bingham and Hughes* [2008] and *Kanzow et al.* [2008] found that at 42°N and 16°N, respectively, interannual variability was dominated by changes at the western boundary. Here we use a simple linear regression between SLA in the west only, at 30°N and 70°W, to develop a proxy for UMO transport.

The transbasin transport proxy (UMO*) shows many of the same features as the observed transports from RAPID, including a relatively weak southward flow in 2005, and more intense southward flow in 2009/2010 and 2012 (Figure 3). While the SLA proxy neglects any explicit contribution from the eastern boundary, barotropic compensation, or wedge transports, the correlation is statistically significant ($r = 0.92$, Figure 3). During the RAPID period, there was a clear shift from a weaker to a stronger UMO. Removing a linear trend over 2004–2014 from both time series, prior to calculating the correlation, still gives a significant correlation with $r = 0.82$.

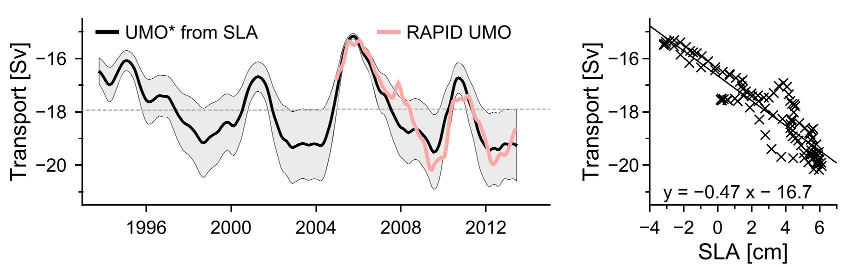

Figure 3. (left) Time series of UMO transport from RAPID (pink) and the SLA proxy, UMO* (black) based on linear regression between UMO and SLA. Gray shading indicates uncertainty associated with the slope of the regression. The dashed grey lines mark the mean of UMO* over the two decades, 1993–2003 and 2004–2014. (right) Scatterplot between the SLA centered at 30°N, 70°W and UMO transport ($r = 0.92$), with the best fit linear regression overlaid and 95% confidence.

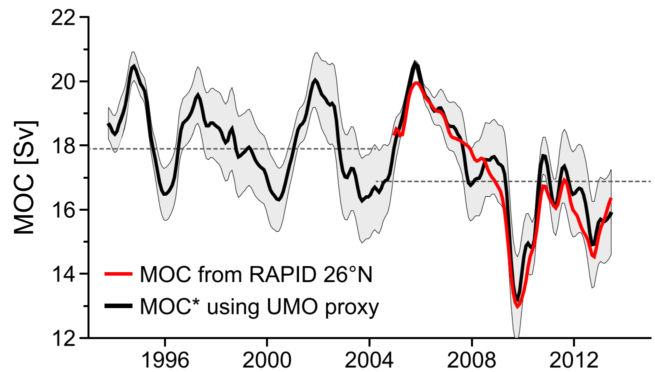

Figure 4. MOC transports from RAPID 26°N (red) and estimated, MOC*, from the SLA proxy for UMO (black). Gray shading indicates the uncertainty associated with the slope of the regression between SLA and UMO. The dashed grey lines mark the means for the two decades, 1993–2003 and 2004–2014. While MOC and MOC* are not independent (both contain the Florida Current and Ekman transport), the correlation coefficient between them is $r = 0.96$.

Before 2004, we see that the UMO* was also strong and that the apparent reduction over the RAPID period of observations from 2004 to 2012 may arise from an anomalously weak UMO in 2005/2006 rather than a continued strengthening of the UMO in the latter part of the record. Indeed, comparing the decades 1993–2003 and 2004–2014, the mean UMO* was −17.8 ± 1.0 Sv and −18.0 ± 1.3 Sv, respectively, with a difference of less than 0.1 Sv.

Following the RAPID methodology, the MOC is estimated as the sum of the UMO transport, the Florida Current transport, and surface Ekman transport. The Florida Current has been measured since 1982 [*Meinen et al.*, 2010] and the ERA-Interim product used to estimate Ekman transports is available since 1979. Replacing the UMO with our UMO* proxy, we can estimate the time-varying MOC since 1993 (MOC*).

The SLA-derived estimate for the MOC captures the interannual variability measured by the RAPID array (2004–2014) with a variance explained of over 90% (Figure 4). Estimating a trend from the extended proxy (1993–2014), we find that there is an average reduction of the MOC of −0.13 Sv/yr (not significant) compared to an estimated reduction from RAPID (2004–2012) of −0.5 Sv/yr [*Smeed et al.*, 2014]. For the 1993–2003 period, the MOC proxy has a mean and standard deviation of 18.3 ± 1.1 Sv, compared to the 2004–2014 period of 17.1 ± 1.7 Sv. While the UMO* did not change, the Florida Current reduced from 32.3 ± 1.3 Sv to 31.4 ± 0.4 Sv. Ekman transport remained relatively constant at 3.8 ± 0.7 and 3.7 ± 0.9 Sv.

4. Conclusions and Discussion

The statistical relationship derived between SLA and transports recovers over 80% of the interannual variations in the upper 1100 m, transbasin transports at 26°N. Comparing the 10 year record of transports from RAPID and spatially smoothed, gridded SLA from altimetry, a negative correlation was identified, centered at 30°N, 70°W. Combining this SLA-based proxy for transbasin transport with cable measurements of the Florida Current and surface Ekman transport, an estimate for the interannual variability of the MOC since 1993 was constructed.

These findings were built on previous investigations into SLA and transports. Previously at 26°N, considering the full SLA and RAPID transport variability from 2004 to 2009, SLA was not found to be a good proxy for transport [*Ivchenko et al.*, 2011]. Part of the breakdown in the relationship between transport and SLA may be attributable to the strong seasonal cycle present in SLA and not measured by subsurface RAPID moorings. In addition, subannual barotropic fluctuations contribute to SLA but not dynamic height and may complicate the relationship between SLA and dynamic height-derived transports. Filtering the time series to consider interannual variations only, we have avoided some of the previous complications. However, this dependence of the SLA-to-transport relationship on time scale does raise questions as to whether a good relationship identified between western boundary SLA and transbasin transports on interannual time scales is equally representative of transport variations on longer time scales. Further work is needed to elucidate the relationship between transbasin transports and SLA.

This new 21 year estimate of MOC variability at 26°N shows a reduction of roughly 1 Sv between the first and latter decades. Unlike interannual and secular variations associated with the UMO over the 2004–2014 period, this reduction arises primarily from a change in the Florida Current. Curiously, the slight reduction estimated here opposes the slight strengthening of the MOC at 41°N also estimated from altimetry [*Willis*, 2010] suggesting a divergence between the two latitudes. In 2009/2010, a slowdown of the MOC at 26°N coincided with an intensification at 41°N, resulting in an intense heat flux divergence and subsequent cooling of the North Atlantic [*Cunningham et al.*, 2014].

While the calculations here are purely statistical, they are rooted in expectations for zonal gradients in pressure (dynamic height or SLA) to govern transport. Despite potential limitations and the relatively short period of intercomparison (10 years), the agreement between the observed UMO transport at 26°N and SLA suggests that a broader view of ocean circulation may be possible, across the North Atlantic and over two decades. Further work is needed to understand over what regions and time scales of variability transports can be estimated from SLA.

These investigations complement the widespread, international efforts to make in situ, continuous measurements of transport variability at a range of latitudes in the Atlantic, including the Meridional Overturning Variability Experiment (MOVE) 16°N [*Send et al.*, 2011], Line W [*Toole et al.*, 2011], RAPID-Western Atlantic Variability Experiment (RAPID-WAVE) [*Elipot et al.*, 2013], South Atlantic Meridional Overturning Circulation (SAMOC) in the South Atlantic [*Meinen et al.*, 2013], and Overturning in the Subpolar North Atlantic Program (OSNAP) in the subpolar North Atlantic. Given the importance of the MOC, and international efforts to measure transports at a range of latitudes, the need and opportunity has never been greater to broaden our spatial view of the circulation across the Atlantic.

Acknowledgments
RAPID is funded by the Natural Environment Research Council in the UK and the National Science Foundation and National Oceanic and Atmospheric Administration in the USA. Data are freely available from http://www.rapid.ac.uk. The DT-MSLA altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.altimetry.fr/duacs/). The 1992–2002 mean ocean dynamic topography data have been obtained from Nikolai Maximenko (IPRC) and Peter Niiler (SIO). Many thanks to H.L. Bryden, J.J.-M. Hirschi, and A. Duchez for helpful discussions.

The Editor thanks Christopher Piecuch and an anonymous reviewer for their assistance in evaluating this paper.

References

Bingham, R. J., and C. W. Hughes (2008), Determining North Atlantic meridional transport variability from pressure on the western boundary: A model investigation, *J. Geophys. Res.*, *113*, C09008, doi:10.1029/2007JC004679.

Bingham, R. J., and C. W. Hughes (2009), Signature of the Atlantic meridional overturning circulation in sea level along the East Coast of North America, *Geophys. Res. Lett.*, *36*, L02603, doi:10.1029/2008GL036215.

Bryden, H. L., H. R. Longworth, and S. A. Cunningham (2005), Slowing of the Atlantic meridional overturning circulation at 25°N, *Nature*, *438*, 655–657.

Clément, L., E. Frajka-Williams, Z. B. Szuts, and S. A. Cunningham (2014), The vertical structure of eddies and Rossby waves and their effect on the Atlantic meridional overturning circulation at 26°N, *J. Geophys. Res. Oceans*, *119*, 6479–6498, doi:10.1002/2014JC010146.

Cunningham, S. A., et al. (2007), Temporal variability of the Atlantic meridional overturning circulation at 26.5°N, *Science*, *317*, 935–938.

Cunningham, S. A., C. Roberts, E. Frajka-Williams, W. E. Johns, W. Hobbs, M. D. Palmer, D. Rayner, D. A. Smeed, and G. D. McCarthy (2014), Atlantic MOC slowdown cooled the subtropical ocean, *Geophys. Res. Lett.*, *40*, 6202–6207, doi:10.1002/2013GL058464.

Elipot, S., C. Hughes, S. Olhede, and J. Toole (2013), Coherence of western boundary pressure at the RAPID WAVE array: Boundary wave adjustments or deep western boundary current advection?, *J. Phys. Oceanogr.*, *43*, 744–765.

Frajka-Williams, E., W. E. Johns, C. S. Meinen, L. M. Beal, and S. A. Cunningham (2013), Eddy impacts on the Florida Current, *Geophys. Res. Lett.*, *40*, 349–353, doi:10.1002/grl.50115.

Hall, M. M., and H. L. Bryden (1982), Direct estimates and mechanisms of ocean heat transport, *Deep Sea Res., Part A*, *29*, 339–359.

Hirschi, J. J. -M., P. D. Killworth, and J. R. Blundell (2007), Subannual, seasonal and interannual variability of the North Atlantic meridional overturning circulation, *J. Phys. Oceanogr.*, *37*, 1246–1265, doi:10.1175/JPO3049.1.

Hobbs, W., and J. K. Willis (2012), Midlatitude North Atlantic heat transport: A time series based on satellite and drifter data, *J. Geophys. Res.*, *117*, C01008, doi:10.1029/2011JC007039.

Ivchenko, V. O., D. Sidorenko, S. Danilov, M. Losch, and J. Schröter (2011), Can sea surface height be used to estimate oceanic transport variability?, *Geophys. Res. Lett.*, *38*, L11601, doi:10.1029/2011GL047387.

Johns, W. E., et al. (2011), Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N, *J. Clim.*, *24*, 2429–2449.

Kanzow, T., S. A. Cunningham, D. Rayner, J. J. -M. Hirschi, W. E. Johns, M. O. Baringer, H. L. Bryden, L. M. Beal, C. S. Meinen, and J. Marotzke (2007), Observed flow compensation associated with the MOC at 26.5°N in the Atlantic, *Science*, *317*, 938–941, doi:10.1126/science.1141293.

Kanzow, T., U. Send, and M. McCartney (2008), On the variability of the deep meridional transports in the tropical North Atlantic, *Deep Sea Res., Part I*, *55*, 1601–1623.

Kanzow, T., et al. (2010), Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N, *J. Clim.*, *23*, 5678–5698, doi:10.1175/2010JCLI3389.1.

Longworth, H. R., H. L. Bryden, and M. O. Baringer (2011), Historical variability in Atlantic meridional baroclinic transport at 26.5°N from boundary dynamic height observations, *Deep Sea Res., Part II*, *58*, 1754–1767.

McCarthy, G., E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. D. Roberts, and S. A. Cunningham (2012), Observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N, *Geophys. Res. Lett.*, *39*, L19609, doi:10.1029/2012GL052933.

McCarthy, G. D., D. A. Smeed, W. E. Johns, E. Frajka-Williams, B. I. Moat, D. Rayner, M. O. Baringer, C. S. Meinen, and H. L. Bryden (2015), Measuring the Atlantic meridional overturning circulation at 26°N, *Prog. Oceanogr.*, *130*, 91–111.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U. K., and New York.

Meinen, C. S., M. O. Baringer, and R. F. Garcia (2010), Florida Current transport variability: An analysis of annual and longer-period signals, *Deep Sea Res., Part I*, *57*, 835–846.
Meinen, C. S., S. Speich, R. C. Perez, S. Dong, A. R. Piola, S. L. Garzoli, M. O. Baringer, S. Gladyshev, and E. J. D. Campos (2013), Temporal variability of the meridional overturning circulation at 34.5°S: Results from two pilot boundary arrays in the South Atlantic, *J. Geophys. Res. Oceans*, *118*, 6461–6478, doi:10.1002/2013JC009228.
Piecuch, C. G., and R. M. Ponte (2011), Mechanisms of interannual steric sea level variability, *Geophys. Res. Lett.*, *38*, L15605, doi:10.1029/2011GL048440.
Piecuch, C. G., K. J. Quinn, and R. M. Ponte (2013), Satellite-derived interannual ocean bottom pressure variability and its relation to sea level, *Geophys. Res. Lett.*, *40*, 3106–3110, doi:10.1002/grl.50549.
Roberts, C. D., L. Jackson, and D. McNeall (2014), Is the 2004–2012 reduction of the Atlantic meridional overturning circulation significant?, *Geophys. Res. Lett.*, *41*, 3204–3210, doi:10.1002/2014GL059473.
Send, U., M. Lankhorst, and T. Kanzow (2011), Observation of decadal change in the Atlantic meridional overturning circulation using 10 years of continuous transport data, *Geophys. Res. Lett.*, *38*, L24606, doi:10.1029/2011GL049801.
Smeed, D. A., et al. (2014), Observed decline of the Atlantic meridional overturning circulation 2004 to 2012, *Ocean Sci.*, *10*, 29–38, doi:10.5194/os-10-29-2014.
Toole, J. M., R. G. Curry, T. M. Joyce, M. McCartney, and B. Peña-Molino (2011), Transport of the North Atlantic deep western boundary current about 39°N, 70°W: 2004–2008, *Deep Sea Res., Part II*, *38*, 1768–1780.
Vinogradova, N. T., R. M. Ponte, and D. Stammer (2007), Relation between sea level and bottom pressure and the vertical dependence of oceanic variability, *Geophys. Res. Lett.*, *34*, L03608, doi:10.1029/2006GL028588.
Willis, J. K. (2010), Can in situ floats and satellite altimeters detect long-term changes in Atlantic Ocean overturning?, *Geophys. Res. Lett.*, *37*, L06602, doi:10.1029/2010GL042372.