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Key Points:
- Overturning slowdown decreases heat and freshwater transport
- Agulhas Leakage is likely source of decreased heat transport
- Freshwater convergence is not causing AMOC slowdown

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

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Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports

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Abstract Recent measurements of the strength of the Atlantic overturning circulation at 26°N show a 1 year drop and partial recovery amid a gradual weakening. To examine the extent and impact of the slowdown on basin wide heat and freshwater transports for 2004–2012, a box model that assimilates hydrographic and satellite observations is used to estimate heat transport and freshwater convergence as residuals of the heat and freshwater budgets. Using an independent transport estimate, convergences are converted to transports, which show a high level of spatial coherence. The similarity between Atlantic heat transport and the Agulhas Leakage suggests that it is the source of the surface heat transport anomalies. The freshwater budget in the North Atlantic is dominated by a decrease in freshwater flux. The increasing salinity during the slowdown supports modeling studies that show that heat, not freshwater, drives trends in the overturning circulation in a warming climate.

1. Introduction

The meridional transports of heat and freshwater in the Atlantic Ocean are intimately linked to strength of the Atlantic Meridional Overturning Circulation (AMOC) [*Ganachaud and Wunsch*, 2003]. The net meridional property transports are a consequence of the large temperature and salinity differences between the surface waters flowing northward and the deep water returning southward. Heat converging in the South Atlantic from both the Indian and Pacific Oceans is transported northward to the high latitudes, where it modifies the European climate. Freshwater from the Arctic and high-latitude North Atlantic flows southward into the Southern Ocean. Many climate models predict a future decrease in the AMOC, which would decrease heat and freshwater transports, with consequences for climate and a possible feedback to further slow the AMOC [*Kirtman et al.*, 2013; *Jackson et al.*, 2015].

Recent observations from the Rapid Climate Change Programme (RAPID) array at 26.5°N [*Cunningham et al.*, 2007] and the associated Meridional Overturning and Heatflux Array (MOCHA) program [*Johns et al.*, 2011] show a drop and partial recovery in AMOC strength in 2010–2011, with contributions from Ekman and interior geostrophic transports, as well as a gradual AMOC weakening since 2004, primarily from the interior flow [*McCarthy et al.*, 2012; *Smeed et al.*, 2014]. The AMOC anomaly produced a large drop in northward heat transport (MHT) and a decrease in southward freshwater transport [*McDonagh et al.*, 2015]. During this period freshwater input into the Atlantic by melting glaciers and ice sheets has been increasing [*Enderlin et al.*, 2014], while salinity is also increasing [*Rhein et al.*, 2013].

To examine the impact of the recent slowdown of AMOC at the RAPID array on meridional heat and freshwater transports throughout the Atlantic basin, we have modified the methodology of a previous study by *Kelly et al.* [2014] (hereafter KTL). That study showed that the MHT anomalies are meridionally coherent and suggested a southern source. As the largest contributor to anomalies in the South Atlantic heat budget are the warm waters of the Agulhas Leakage [*Dong et al.*, 2011], we investigate its role in MHT as suggested by the modeling studies of *Biastoch et al.* [2008], *Heimbach et al.* [2011], *Beal et al.* [2011], and *Biastoch et al.* [2015]. Here we retain the heat budget of KTL and replace the mass budget with a freshwater budget in each of four Atlantic-spanning regions, delineated by the latitude lines: 67°N, 40°N, 25°N, 10°S, and 35°S (Figure 1).

2. Methods

Following the KTL methodology, we model here the Atlantic nonseasonal heat and freshwater budgets in terms of sea level components. Anomalies of ocean steric height can be measured from satellite or from in

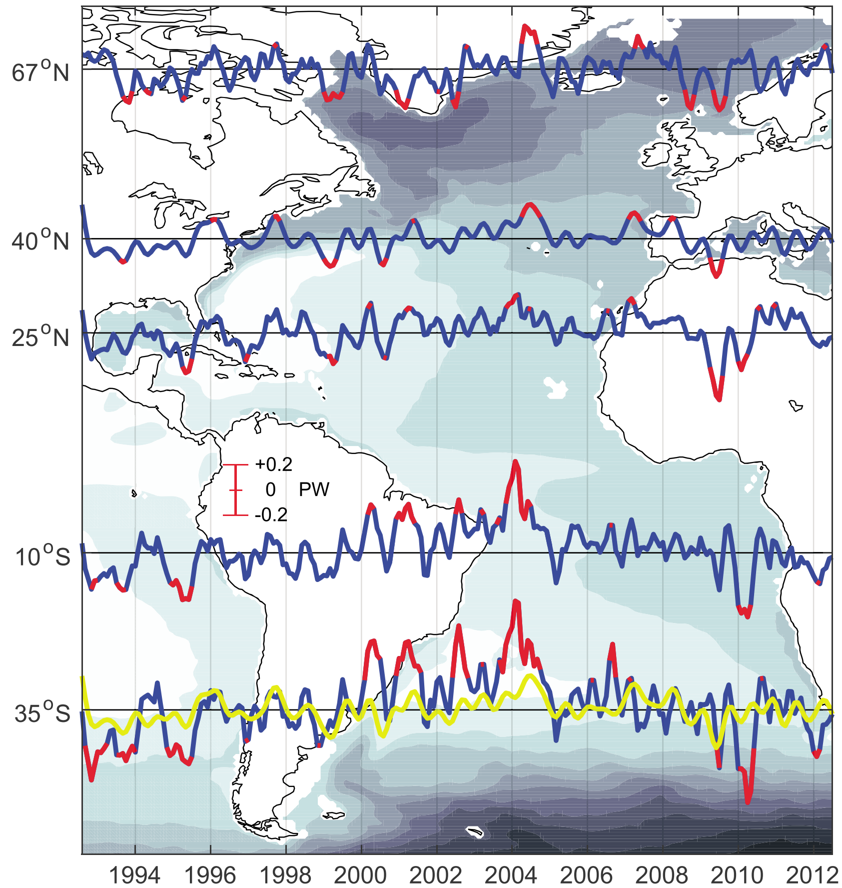

Figure 1. Meridional heat transport anomalies from the box model (blue) at 67°N, 40°N, 25°N, 10°S, and 35°S. Latitude lines delineate the four regions over which budgets were estimated. Red overplotting indicates periods when the modeled MHT exceeds the estimated error. MHT at 41°N derived from estimates by *Willis* [2010] is repeated (yellow) at 35°S for comparison. Mean sea surface height from Aviso contoured at intervals of 0.1 m for reference. Units are petawatts (PW).

situ observations, which should be equivalent as

$$\mathrm{SSH} - \mathrm{OM} = \mathrm{TSL} + \mathrm{HSL} \tag{1}$$

where the left-hand side is sea surface height (SSH) minus ocean mass (OM) and the right-hand side is thermosteric (TSL) plus halosteric sea level (HSL). The satellite components are derived from radar altimeters and from the Gravity Recovery and Climate Experiment (GRACE) satellite since 2002, respectively; the in situ components from hydrographic data, predominantly Argo since 2004.

The heat budget is written in terms of the thermosteric component of sea level η_T as

$$\frac{\partial \eta_T}{\partial t} = \frac{\alpha Q_{\mathrm{net}}}{\rho_0 c_p} + U_T \tag{2}$$

where Q_{net} is the net surface heat flux into the ocean, α is the coefficient of thermal expansion, ρ_0 the density, and c_p the heat capacity of seawater. The residual, the convergence of thermosteric sea level, is denoted U_T. See supporting information S1 on how we estimate α.

The freshwater budget is written in terms of the halosteric component of sea level η_S as

$$\frac{\partial \eta_S}{\partial t} = \beta S_o (P - E) + U_S \tag{3}$$

where S_o is a reference salinity value, β is the coefficient of saline contraction, P is precipitation, E is evaporation, and the difference $P - E$ is the net freshwater flux into the ocean. The residual U_S is the convergence of

Table 1. Fields Used in Model

Field	Name	Source[a]	Resolution
Turbulent flux	OAFlux	WHOI	0.5°, daily
Radiative flux	SRB/GEWEX	NASA/Langley	1°, monthly
Radiative flux	CERES/EBAF	NCAR	1°, monthly
Net heat flux	NOCS	NOCS	1°, monthly
Net heat flux	ERA Interim	NCAR	1°, monthly
Sea level	SSH	Aviso	0.25°, weekly
Thermosteric sea level	EN3 TSL	UK Met Office	1°, monthly
Halosteric sea level	EN3 HSL	UK Met Office	1°, monthly
Ocean mass	RL05M	JPL	100 km, monthly
Precipitation	GPCP	NASA/GSFC	1°, daily
Evaporation	OAFlux	WHOI	1°, daily
Net freshwater flux	ERA Interim	NCAR	1°, monthly
River discharge	Total Atlantic	GRDC	annual

[a]WHOI, Woods Hole Oceanographic Institution; NCAR, National Center for Atmospheric Research; NOCS, National Oceanography Centre Southampton; JPL, Jet Propulsion Laboratory; GSFC, Goddard Space Flight Center; GRDC, Geological Research and Development Center.

halosteric sea level, which includes contributions from ice and glacier melt and river discharge as well as from ocean circulation.

The model is an "unknown control" version of a Kalman filter in which the vertically integrated heat and freshwater budgets are forced by surface fluxes and TSL and HSL are assimilated. Although the accuracy of the TSL and HSL components is limited by the nominal depth to which Argo profiles sample (usually about 2000 m), a requirement that $\eta_T + \eta_S$ match SSH-OM makes an adjustment to allow for deeper anomalies. A running estimate of model error is used in conjunction with observation error estimates to determine how much the prediction is adjusted to match the observations. See supporting information S1 for error estimates. The residuals U_T and U_S are converted into heat transport convergence (HTC) and freshwater convergence (FWC), which have the more familiar units of petawatts (PW) (1 PW = 10^{15} W) and sverdrups Sv (1 Sv = 10^6 m^3 s^{-1}), respectively.

A baseline model run for 1993–2012 was forced by OAFlux turbulent fluxes plus satellite-based radiative fluxes and Global Precipitation Climatology Project (GPCP) combined with OAFlux evaporation (Table 1). The model produced temporally smoothed versions of sea level components and estimates of heat and freshwater convergence. Modeled thermosteric sea level η_T closely tracks SSH-OM, with halosteric sea level η_S making a smaller contribution (Figure S1).

Transports at each region boundary (Figure 1) were derived by integrating the convergences southward from the northernmost region and adding a time-varying integration constant. The constant was obtained by differencing an independent transport estimate and the cumulative convergences at the latitude of the transport. For the heat budget we derived MHT at 41°N for 1993–2012 from a regression with the MOC estimates by *Willis* [2010], based on Argo and SSH (More detail in supporting information S1). The 41°N MHT is repeated as a yellow line at 35°S in Figure 1 for comparison with MHT at 35°S. Freshwater transport (FWT) was derived analogously for 2004–2012 from an estimate at the RAPID array at 26.5°N [*McDonagh et al.*, 2015, Figure 4].

Additional model runs tested the sensitivity of the model to forcing by ERA interim or by National Oceanography Centre Southampton (NOCS) net surface heat fluxes (Table 1). MHT estimates from the three products (Figure 2) have similar interannual variability and a high level of spatial coherence (See supporting information S1 and Figure S2). Discrepancies are small at 25°N (Figure 2a), where the constraint to match the MHT at 41°N is strong and increase southward reflecting the cumulative differences in flux products (Figure 2b). Observed MHT trends for 2004–2012 are −0.17 PW/decade at 41°N increasing to nearly double that at the RAPID/MOCHA array (−0.32 PW/decade). At 35°S the baseline fluxes give a negative trend

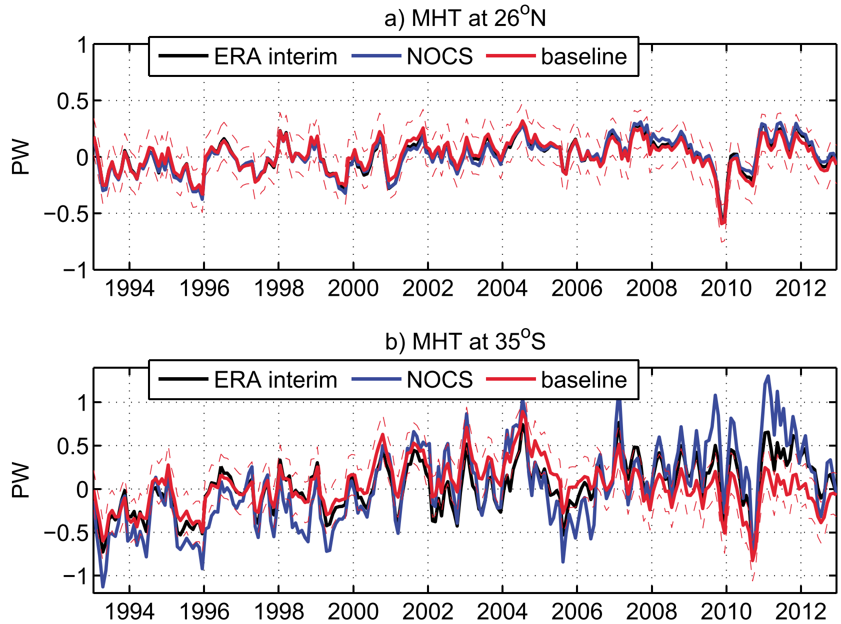

Figure 2. Sensitivity of meridional heat transport estimates to different flux products. Baseline using OAFlux turbulent plus satellite-based radiative (red), ERA interim (black), and NOCS (blue) for (a) 25°N and (b) 35°S. Error bars for baseline MHT (dashed). Units are petawatts (PW).

twice that of MOCHA (−0.62 PW/decade), the ERA Interim fluxes give a near-zero trend and the NOCS fluxes give a large positive trend (0.41 PW/decade). Consistency with the negative MHT trends in the observations motivated the use of the baseline heat fluxes in further analyses.

3. Results and Discussion

Distinctive anomalies in convergences and meridional transports at all latitudes coincided with the 2010–2011 AMOC event. The MHT estimates at 25°N from all model runs reproduced the MHT minimum [*Johns et al.*, 2011] (Figures 2a and 3) with discrepancies that are mostly within our error bars. The AMOC minimum was also associated with a decrease in southward FWT [*McDonagh et al.*, 2015], with convergence to the north of 25°N and divergence to the south. Here we find that positive HTC anomalies occurred in the 10°S–25°N region, consistent with a deepening of the thermocline at 75°W in the RAPID array [*McCarthy et al.*, 2012], with a small divergence to the north.

Atlantic-wide trends in the heat and freshwater transports coincided with the decline in AMOC over the Argo period, 2004–2012. To determine the role of the Agulhas Leakage (AL) in negative MHT trends, monthly net volume transport anomalies were estimated as in *Le Bars et al.* [2014] using along-track SSH (Figure 4a). Monthly net transports (westward flow minus eastward flow) from the coast to the South Atlantic Current

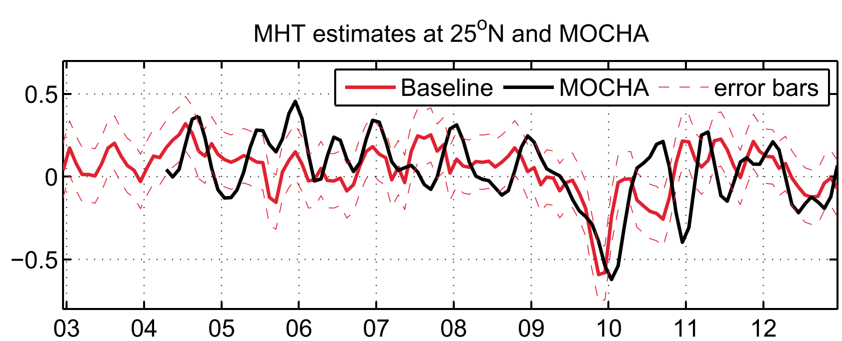

Figure 3. Modeled and observed MHT anomalies at RAPID line. Baseline run MHT estimate at 25°N (red) and estimates from MOCHA at 26.5°N (black). Error bars for model (dashed).

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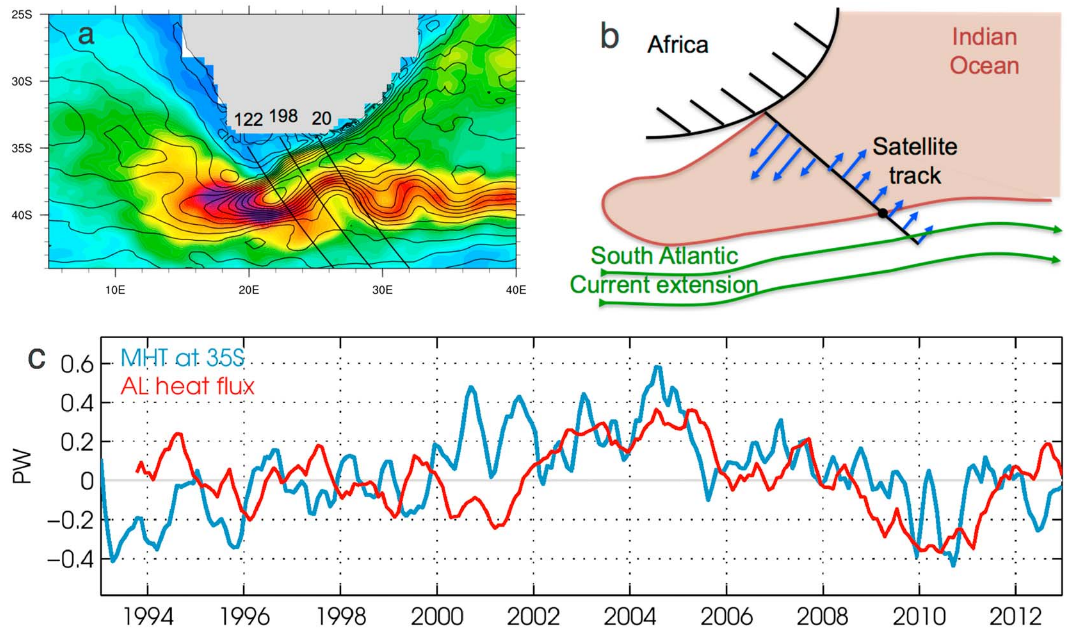

Figure 4. MHT and Agulhas Leakage. (a) SSH map and altimeter tracks and (b) schematic of net leakage across an altimeter track. (c) Baseline MHT (blue) at 35°S and inferred Agulhas Leakage heat transport (red).

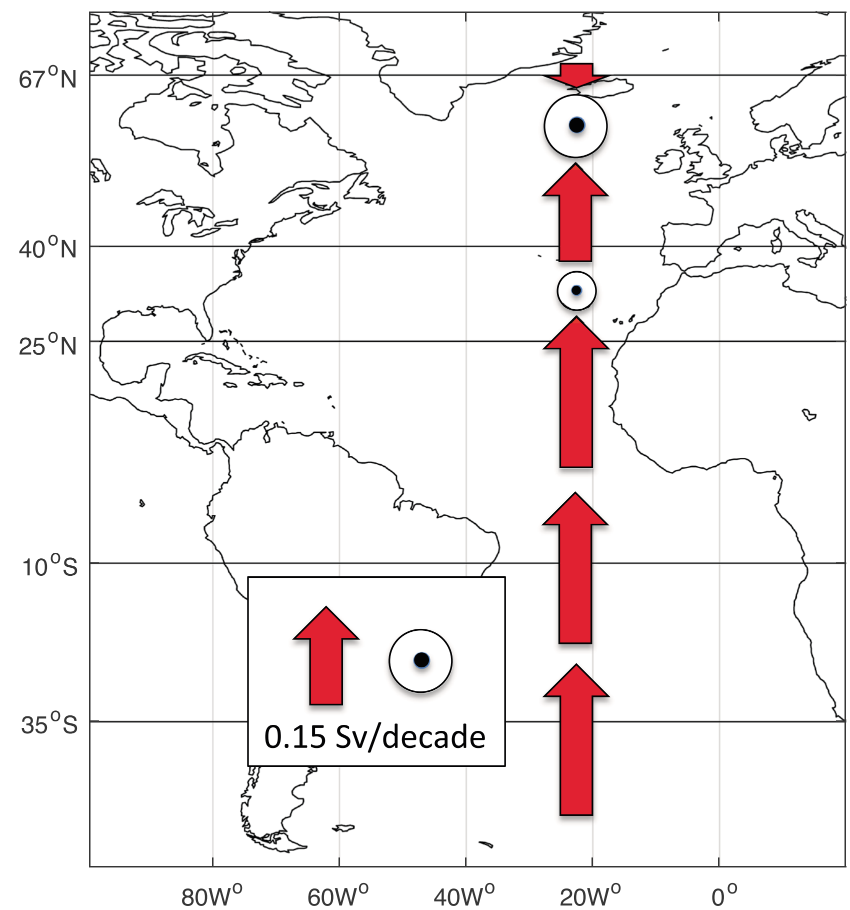

Figure 5. Trends in freshwater budget for 2004–2012. Trends in freshwater transport (arrows) and convergence (FWC, dots) across the boundaries and within four regions, respectively. Trends in FWC are negligible except in the two northernmost regions. Units are Sv/decade with scale in insert.

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Extension (Figure 4b) were low-pass filtered to remove seasonal anomalies and converted to heat transport estimates using a coefficient of 0.05 PW/Sv, a value derived from Atlantic XBT transects near 35°S by *Dong et al.* [2009].

The net heat transport (Figure 4c, red line) is similar in magnitude and phase to our MHT estimate (blue line) in the post-Argo period (2004–2012). The correlation between AL and MHT for 1993–2012 is 0.4 with zero lag at 35°S, decreasing northward but significant at 95% for all latitudes, suggesting that the AL is supplying the Atlantic MHT anomalies. The lack of a lag in MHT between latitudes suggests an adjustment of the circulation by Kelvin waves, as opposed to a slower advective response [*Biastoch et al.*, 2008; *Zhang*, 2010]. This adjustment may be seen in the heaving of the ocean thermocline at the RAPID array, and this mechanism is supported by a recent study of historical hydrographic data, which showed that heat transport convergence is usually associated with the sinking of the thermocline, particularly in the subtropical gyres [*Häkkinen et al.*, 2015].

Southward FWT decreases at all latitudes during 2004–2012, consistent with a slowdown of the AMOC. FWT trends for the baseline run are about 0.24 Sv/decade at 25°N, 10°S, and 35°S (Figure 5); that is, southward FWT is weakening. A sustained trend of more than 0.2 Sv/decade would reverse the sign of the FWT to northward at 35°S, where the mean has been estimated as southward at 0.2 Sv [*Weijer et al.*, 1999].

The trend toward less southward FWT is smaller in the North Atlantic, giving rise to increasing FWC (0.15 Sv/decade) for 40°N–67°N (Figure 5). Similar FWT trends were found using ERA Interim freshwater flux (Table 1; see supporting information S1 and Figure S3a), but the FWT trends are more spatially uniform so there is less convergence. The relatively small trends in freshwater contributions from the Greenland Ice Sheet of 0.008 Sv/decade (26 Gta per year [*Enderlin et al.*, 2014]) and from river discharge (1993–2009) of 0.01 Sv/decade suggest that the FWC trend is primarily from the change in ocean circulation. The increase in FWC north of 40°N (Figure S1b, black line) from 2004–2012 is not sufficient to create a freshwater anomaly there, owing to a pre-existing positive salinity anomaly and to a decrease in surface freshwater flux (Figure S3b, red line) beginning in about 1994 [*Boyer et al.*, 2007]. Therefore, in this period for which we have detailed observations, the slowdown of the AMOC is apparently not caused by a freshwater anomaly in the North Atlantic.

4. Conclusions

A box model of the Atlantic heat and freshwater budgets during a period of slowdown of the AMOC yields estimates of meridional heat and freshwater transport. The analysis is enabled by improvements in surface forcing fields and in observations of ocean properties; results are remarkably robust with respect to the choice of surface forcing products. 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.

The similarities in timing and magnitude between Atlantic MHT and the Agulhas Leakage suggest that the AMOC slowdown extends into the Agulhas Current system and that the AL is the source of the decade-long heat transport decrease, consistent with the modeling results of *Biastoch et al.* [2015] for longer time scales.

The trend toward weaker freshwater transport, 0.24 Sv/decade, is sufficiently large and coherent to reverse the mean southward freshwater transport at 35°S. 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 [*Gregory et al.*, 2005; *Weaver et al.*, 2007].

References

Beal, L. M., W. P. M. D. Ruijter, A. Biastoch, R. Zahn, and SCOR/WCRP/IAPSO Working Group 36 (2011), On the role of the Agulhas system in ocean circulation and climate, *Nature*, *472–436*, doi:10.1038/nature09983.

Biastoch, A., C. W. Böning, and J. R. E. Lutjeharms (2008), Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation, *Nature*, *456*(27), 489–492, doi:10.1038/nature07426.

Biastoch, A., J. V. Durgadoo, A. K. Morrison, E. van Sebille, W. Weijer, and S. M. Griffies (2015), Atlantic multi-decadal oscillation covaries with Agulhas leakage, *Nat. Commun.*, *6*, 10082, doi:10.1038/ncomms10082.

Boyer, T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, and S. A. Josey (2007), Changes in freshwater content in the North Atlantic Ocean 1955–2006, *Geophys. Res. Lett.*, *34*, L16603, doi:10.1029/2007GL030126.

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

Dong, S., S. Garzoli, M. Baringer, C. Meinen, and G. Goni (2009), Interannual variations in the Atlantic meridional overturning circulation and its relationship with the net northward heat transport in the South Atlantic, *Geophys. Res. Lett.*, *36*, L20606, doi:10.1029/2009GL039356.

Dong, S., S. Garzoli, and M. O. Baringer (2011), The role of interocean exchanges on decadal variations of the meridional heat transport in the South Atlantic, *J. Phys. Oceanogr.*, *41*, 1498–1511, doi:10.1175/2011JPO4549.1.

Enderlin, E. M., I. M. Howat, S. Jeong, M.-J. Noh, J. H. van Angelen, and M. R. van den Broeke (2014), An improved mass budget for the Greenland ice sheet, *Geophys. Res. Lett.*, *41*, 866–872, doi:10.1002/2013GL059010.

Ganachaud, A., and C. Wunsch (2003), Large-scale ocean heat and freshwater transports during the World Ocean Circulation Experiment, *J. Clim.*, *16*, 696–705.

Gregory, J. M., et al. (2005), A model intercomparison of changes in Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, *Geophys. Res. Lett.*, *32*, L12703, doi:10.1029/2005GL023209.

Häkkinen, S., P. B. Rhines, and D. L. Worthen (2015), Heat content variability in the North Atlantic Ocean in ocean reanalyses, *Geophys. Res. Lett.*, *42*, 2901–2909, doi:10.1002/2015GL063299.

Heimbach, P., C. Wunsch, R. Ponte, G. Forget, C. Hill, and J. Utke (2011), Timescales and regions of the sensitivity of Atlantic meridional volume and heat transport: Toward observing system design, *Deep Sea Res., Part II*, *58*, 1858–1879.

Jackson, L. C., R. Kahana, T. Graham, M. A. Ringer, T. W. áandJ. V. Mecking, and R. A. Wood (2015), Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, *Clim. Dyn.*, *45*, 3299–3316, doi:10.1007/s00382-015-2540-2.

Johns, W., M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, H. L. Bryden, J. J. M. Hirschi, J. Marotzke, C. S. Meinen, B. Shaw, and R. Curry (2011), Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N, *J. Clim.*, *24*, 2429–2449.

Kelly, K. A., L. Thompson, and J. Lyman (2014), The coherence and impact of meridional heat transport in the Atlantic Ocean inferred from observations, *J. Clim.*, *27*(4), 1469–1487.

Kirtman, B., et al. (2013), 2013: Near-term climate change: Projections and predictability, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., pp. 953–1028, Cambridge University Press, Cambridge, U. K., and New York.

Le Bars, D., J. V. Durgadoo, H. A. Dijkstra, A. Biastoch, and W. P. M. D. Ruijter (2014), An observed 20-year time series of Agulhas leakage, *Ocean Sci.*, *10*, 601–609, doi:10.5194/os-10-601-2014.

McCarthy, G., E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, 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.

McDonagh, E. L., B. A. King, H. L. Bryden, P. Courtois, Z. Szuts, M. Baringer, S. A. Cunningham, C. Atkinson, and G. McCarthy (2015), Continuous estimate of Atlantic oceanic freshwater flux at 26.5°N, *J. Clim.*, *28*, 8888–8906.

Rhein, M., et al. (2013), Observations: Ocean, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker and other, pp. 255–315, Cambridge Univ. Press, Cambridge, U. K., and New York.

Smeed, D. A., G. D. McCarthy, S. A. Cunningham, E. Frajka-Williams, D. Rayner, W. E. Johns, C. S. Meinen, M. O. Baringer, B. I. Moat, A. Duchez, and H. L. Bryden (2014), Observed decline of the Atlantic meridional overturning circulation 2004-2012, *Ocean Sci.*, *10*, 29–38, doi:10.5194/os-10-29-2014.

Weaver, A. J., M. Eby, M. Kienast, and O. A. Saenko (2007), Response of the Atlantic meridional overturning circulation to increasing atmospheric CO_2: Sensitivity to mean climate state, *Geophys. Res. Lett.*, *34*, L05708, doi:10.1029/2006GL028756.

Weijer, W., W. P. M. de Ruijter, H. A. Dijkstra, and P. J. van Leeuwen (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284.

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.

Zhang, R. (2010), Latitudinal dependence of Atlantic Meridional Overturning Circulation (AMOC) variations, *Geophys. Res. Lett.*, *37*, L16703, doi:10.1029/2010GL044474.