GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 6202–6207, doi:10.1002/2013GL058464, 2013

Atlantic Meridional Overturning Circulation slowdown cooled the subtropical ocean

Stuart A. Cunningham,[1,2] Christopher D. Roberts,[3] Eleanor Frajka-Williams,[4]
William E. Johns,[5] Will Hobbs,[6] Matthew D. Palmer,[3] Darren Rayner,[2]
David A. Smeed,[2] and Gerard McCarthy[2]

Received 28 October 2013; revised 20 November 2013; accepted 23 November 2013; published 11 December 2013.

[1] Observations show that the upper 2 km of the subtropical North Atlantic Ocean cooled throughout 2010 and remained cold until at least December 2011. We show that these cold anomalies are partly driven by anomalous air-sea exchange during the cold winters of 2009/2010 and 2010/2011 and, more surprisingly, by extreme interannual variability in the ocean's northward heat transport at 26.5°N. This cooling driven by the ocean's meridional heat transport affects deeper layers isolated from the atmosphere on annual timescales and water that is entrained into the winter mixed layer thus lowering winter sea surface temperatures. Here we connect, for the first time, variability in the northward heat transport carried by the Atlantic Meridional Overturning Circulation to widespread sustained cooling of the subtropical North Atlantic, challenging the prevailing view that the ocean plays a passive role in the coupled ocean-atmosphere system on monthly-to-seasonal timescales.

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

1. Introduction

[2] The Atlantic Meridional Overturning Circulation (AMOC) is part of the ocean's global overturning circulation, and AMOC variability is linked to climate variability on seasonal to multicentennial timescales [*Delworth and Mann*, 2000]. The AMOC is a meridionally coherent two-layer circulation with warm water flowing northward in the upper 1.1 km compensated by colder water flowing southward at depths between 1.1 and 5 km [*Kuhlbrodt et al.*, 2007]. Typically these opposing flows each transport an annual average of 18 Sv [*Rayner et al.*, 2011], resulting in a meridional heat transport (MHT) through the South Atlantic and across the equator with a maximum of 1.3 PW in the subtropical North Atlantic [*Johns et al.*, 2011]. The AMOC is a major component of Earth's climate system and is responsible for up to 25% of the global ocean-atmosphere meridional heat flux [*Bryden and Imawaki*, 2001]. Much of this heat is released to the atmosphere in the subtropical North Atlantic and combined with the release of locally stored summer heat, maintains the maritime climate of the UK and Western Europe some 5–10°C above the zonal average for these latitudes [*Rahmstorf and Ganopolski*, 1999]. Model simulations have linked AMOC variability to climate impacts on decadal timescales [*Knight*, 2005; *Latif et al.*, 2004], and observations suggest that the AMOC is a fundamental component of the seasonal ocean-atmosphere heat budget [*Rhines et al.*, 2008]. However, until now, direct observational evidence for a link between the AMOC and climate has been lacking. In this study, we exploit recent improvements to the ocean observing system in the North Atlantic to quantify the anomalous ocean MHT associated with a transient weakening of the AMOC and the associated impact on subtropical ocean heat content (OHC).

2. Data and Methods

[3] To investigate the causes of the observed reduction in OHC, we use estimates of ocean and ocean-atmosphere heat fluxes into the subtropical Atlantic Ocean between 26.5 and 41°N to determine the subtropical Atlantic OHC budget. We estimate ocean MHT divergence using the RAPID-Meridional Overturning Circulation and Heat Flux Array (RAPID-MOCHA) heat transport array at 26.5°N [*Baringer and Larsen*, 2001; *Cunningham et al.*, 2007; *Johns et al.*, 2011; *Rayner et al.*, 2011] and heat transports at 41°N derived from available Argo floats and satellite altimetry [*Hobbs and Willis*, 2012; *Willis*, 2010] (see section S1 in the supporting information). Air-sea surface fluxes are obtained from the ERA-interim atmospheric reanalysis [*Dee et al.*, 2011], and we assume that OHC anomalies at depths greater than 2000 m are negligible.

Additional supporting information may be found in the online version of this article.

[1] Now at Scottish Association for Marine Science, Scottish Marine Institute, Oban, UK.

[2] National Oceanography Centre, Southampton, UK.

[3] Met Office Hadley Centre, Exeter, UK.

[4] National Oceanography Centre, University of Southampton Waterfront Campus, Southampton, UK.

[5] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA.

[6] Institute for Marine and Antarctic Studies, ARC Centre of Excellence for Climate System Science, University of Tasmania, Hobart, Tasmania, Australia.

Corresponding author: S. A. Cunningham, Scottish Association for Marine Science, Scottish Marine Institute, Oban PA37 1QA, UK. (Stuart.Cunningham@sams.ac.uk)

0094-8276/13/10.1002/2013GL058464

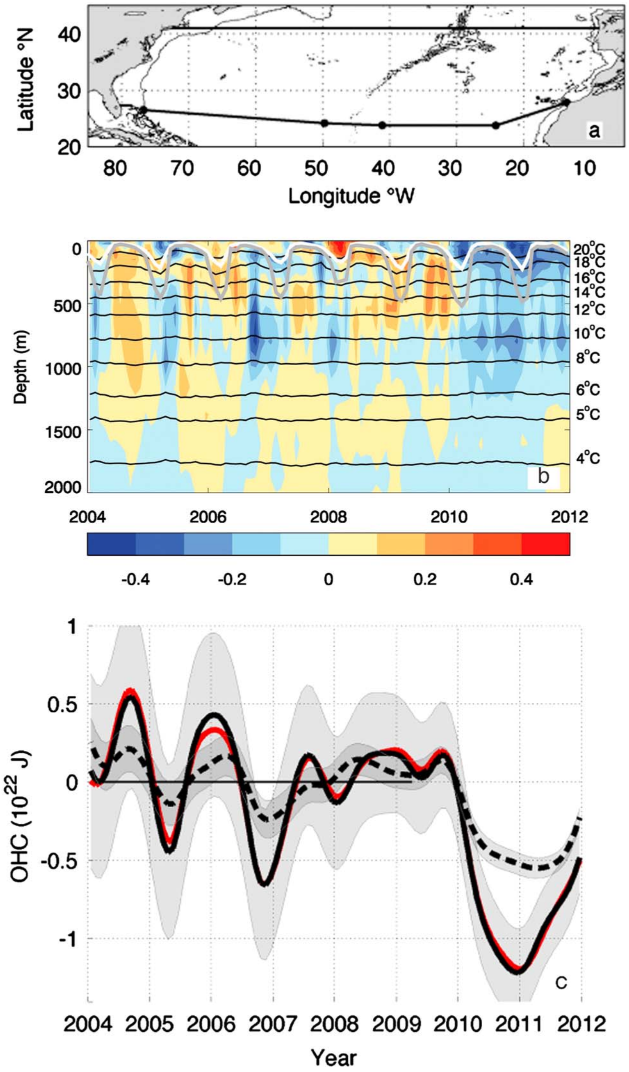

Figure 1. (a) Measurement locations and region of interest. Bathymetry (0 and 2000 m contours) and topography (grey) of the North Atlantic region with the northern and southern limits of the volume shown by black lines at 26.5°N and 41°N. At 26.5°N, the Florida cable is given by the short segment between Florida and the Bahamas, and the principal RAPID 26.5°N array mooring positions are indicated by dots. (b) Area-averaged subsurface temperature anomalies in the subtropical North Atlantic (5–82°W, 26.5–41°N) calculated relative to the 1991–2010 seasonal cycle using monthly means from the EN3 v2a gridded objective analysis of quality-controlled subsurface temperature observations [*Ingleby and Huddleston*, 2007], (http://www.metoffice.gov.uk/hadobs/en3/). Black lines indicate the area-averaged depth of selected isotherms across the same region. Mean mixed layer depth (white) and the 95th percentile (grey) for which only 5% of grid boxes have a deeper mixed layer defined by *Kara et al.* [2000]. The MLD is the depth over which air-sea exchanges drive turbulent mixing of the ocean. (c) Six month low-pass filtered ocean heat content anomalies relative to 1991–2010 above 2000 m (solid black), above the 4°C isotherm (red) and above the 14°C isotherm (dashed black). OHC uncertainties (grey) are generated by model-based estimates associated with changes in sampling density and locations and are for 10 day values. They are approximated by the OHC uncertainties shallower than 2000 m and 500 m respectively (section S3).

[4] To examine the contributions of meridional heat transport and air-sea fluxes, we define an OHC budget as follows (section S2):

$$\mathrm{OHC}(t) - \mathrm{OHC}(t_0) = \int_{t_0}^{t} F' + S' - N'\mathrm{d}t, \qquad (1)$$

where OHC [J] is the ocean heat content, t is time and t_0 is an initial reference time. F' is the air-sea heat flux across the sea surface, S' and N' are ocean MHTs through the southern (26.5°N) and northern (41°N) boundaries, respectively [J $\mathrm{s}^{-1} = \mathrm{W}$], and primes denote anomalies relative to a seasonal climatology. To estimate the seasonal cycle in S', we use the first 5 years of the RAPID-MOCHA observations from 1 April 2004 to 31 March 2009 (the reference period) when a seasonal cycle was robustly present, as shown by *Kanzow et al.* [2010] (section S1), but not using data after April 2009, which include the anomalous variability being investigated. This approach was also taken for N'. However, MHTs and MHT divergence is not sensitive to a reference period spanning the anomalous period (section S1). For F', a much longer reanalysis period from 1991 to 2010 was used to calculate a representative seasonal cycle that was insensitive to the inclusion of data after 2009. F' is also insensitive to a choice of reference period matching the period of S' and N' (section S2). For S' and N', removal of a seasonal cycle estimated during the reference period (by definition) results in a net zero mean for the integrated MHT during the reference period. For F', subsequent to the removal of the seasonal cycle, we adjust the integrated anomalies to have zero mean during the reference period.

3. Subtropical Atlantic Ocean Heat Content

[5] The purposefully designed RAPID-MOCHA array has been measuring the strength and structure of the AMOC at 26.5°N since April 2004 [*Cunningham et al.*, 2007; *Kanzow et al.,* 2007]. These measurements recently revealed that the annual average AMOC decreased by 30% over a 12 month period beginning in April 2009 [*McCarthy et al.*, 2012]. Associated with this transport anomaly, there is a sustained cooling of the upper 2000 m of the subtropical Atlantic Ocean (defined here as the region between 26.5°N and 41°N) (Figure 1a). The most intense cooling was in the mixed layer during the winter months of 2009/2010 and 2010/2011, with temperature anomalies in excess of −0.5°C (Figure 1b). During the summers of 2010 and 2011, warm anomalies were present at the ocean surface, whereas cold temperature anomalies were sustained below the mixed layer depth. From late 2009, subtropical Atlantic OHC decreased over a 12 month (Figure 1c) period to a minimum value of -1.3×10^{22} J, then gradually increased during 2011 to -0.5×10^{22} J. These OHC anomalies are robust to incomplete spatial sampling and are not driven by a systematic change to the observing system (section S3). With the exception of a brief 2 month cool period at the end of 2006 that appears localized to the Gulf Stream location along 41°N (section S4), OHC anomalies do not exceed our empirically derived 95% confidence limits until the persistent cooling from 2010.

[6] The spatial pattern of the OHC decrease is coherent across much of the subtropical Atlantic indicating a large-scale forcing, and is not due simply to a shift in the position of the Gulf Stream (section S5). By July 2010 the negative

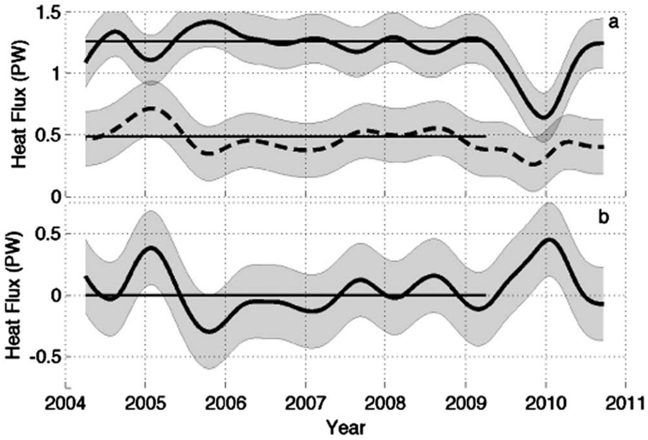

Figure 2. (a) Deseasonalized 6 month low-pass time series of the meridional heat transports [PW] from the RAPID/MOCHA array at 26.5°N (black) [*Johns et al.*, 2011] and from the Argo/altimetric estimate at 41°N (black dashed) [*Hobbs and Willis*, 2012]. The RAPID/MOCHA at 26.5°N data have a temporal resolution of 0.5 days, and 41°N data are 3 monthly. The error (grey) for daily values of heat transport at 26.5°N is 0.2 PW and at 41°N for monthly values is 0.22 PW. Horizontal black lines are the mean of the time series from 1 April 2004 to 31 March 2009. Both time series are deseasonalized by calculating a mean seasonal cycle for the period 1 of April 2004 to 31 March 2009 (section S1). (b) Heat transport divergence (41–26.5°N) set to zero mean in the period 1 April 2004 to 31 March 2009, where values above zero indicate cooling of the subtropical Atlantic. The uncertainty (grey) is the root-sum-square error from 26.5°N and 41°N.

OHC anomaly extends in a broadband across the subtropical gyre, extending southwestward to 11°N in the western Atlantic. The total OHC change in the upper 2000 m can be divided into two approximately equal components: (1) changes in the seasonally mixed layer above the 14°C isotherm where ocean advection and air-sea heat fluxes contribute and (2) changes between 4°C and 14°C that are outside the influence of seasonally mixed layer and air-sea fluxes, indicating a role for advection in driving the observed cooling at depth.

4. Meridional Heat Transport Divergence

[7] The observed MHTs at 26.5°N and 41°N are 1.26 ± 0.11 PW and 0.48 ± 0.11 PW, respectively, for the reference period 1 April 2004 to 31 March 2009 (mean ± SD) (Figure 2a and Table 1). For both latitudes, the AMOC is the dominant mechanism carrying the MHT with the horizontal gyre accounting for 10% and 20% (26.5°N and 41°N respectively) of the total MHT [*Johns et al.*, 2011] (section S6). MHT variability associated with the AMOC is determined almost entirely by circulation changes [*Jayne and Marotzke*, 2001; *Johns et al.*, 2011]. For example, at 26.5°N the correlation between the AMOC and MHT variability is $R^2 = 0.94$ [*Johns et al.*, 2011].

[8] The most striking feature of the observed records of MHT is the large decrease across 26.5°N beginning in April 2009 and continuing through spring 2010. This anomaly is only weakly compensated by reduced export of heat at 41°N (Table 1) and results in a maximum of anomalous MHT divergence during the same time period (Figure 2b). Overall, the interannual variability of MHT to the subtropical Atlantic is dominated by the AMOC strength at 26.5°N. While part of the reduction in 2009/2010 is due to a reversal in Ekman transports caused by the negative NAO in winter 2009/2010, the longer term reduction was driven by an increase in the southward geostrophic transport in the gyre interior [*McCarthy et al.*, 2012].

5. Inferred Ocean Heat Content Change

[9] To calculate the OHC change in the subtropical Atlantic due to changes in ocean MHT and atmospheric heat fluxes, we integrate the ocean MHT divergence between 26.5°N and 41°N and ERA-interim air-sea heat fluxes through time (section S7). OHC decreases abruptly in the last months of 2009 and early 2010 (Figures 3b and 3c), due to MHT divergence and reduced surface fluxes into the subtropical North Atlantic. The relatively abrupt increases in heat loss due to air-sea fluxes in DJF 2009/2010 and December 2010 coincide with two exceptionally negative phases of the NAO, such that increased wind speeds over the subtropical gyre result in large anomalies in latent heat loss to the atmosphere (section S8). In contrast, the MHT divergence anomaly, that we have shown to be dominated by the AMOC at 26.5°N, is more sustained and acts to cool the subtropical Atlantic through 2010.

[10] There is also a positive MHT divergence in 2005 caused by a decrease in MHT at 26.5°N and an increase in MHT at 41°N. While the MHT changes at the individual latitudes are not significant, their combined effect produces a positive MHT divergence of nearly the same magnitude, but shorter duration than in 2009/2010 (Figure 2b). This effect is apparent in the integrated MHT divergence (Figure 3b), which indicates a cooling between 2005 and 2006. However, although there is a corresponding decrease in OHC (Figure 3a), this decrease is not significantly different from zero relative to the estimated error for OHC.

[11] Within errors, the heat budget is balanced, both during the reference period between April 2004 and March 2009 and after April 2009 (Figure 3d). The magnitudes of the energy fluxes quantified indicate that the recent cooling in the subtropical Atlantic is primarily due to a reduction in the AMOC at 26.5°N.

[12] The mean MHT divergence over the subtropical Atlantic derived from the MHT estimates of Figure 2 ($- \pm 0.20$ PW) implies a surface heat loss over the subtropical Atlantic of -74 ± 19 W m^{-2}. This is inconsistent with the time-mean values for ERA-interim air-sea heat

Table 1. Deseasonalized Mean and Standard Deviation of the Meridional Heat Transport at 26.5°N and 41°N and Associated Divergence [PW]

1 April 2004 to 31 March 2009	Mean	SD
26.5°N	1.26	0.11
41°N	0.48	0.11
41–26.5°N	−0.77	0.20
1 April 2009 to 31 March 2010		
26.5°N	0.85	0.26
41°N	0.35	0.14
41–26.5°N	−0.50	0.23

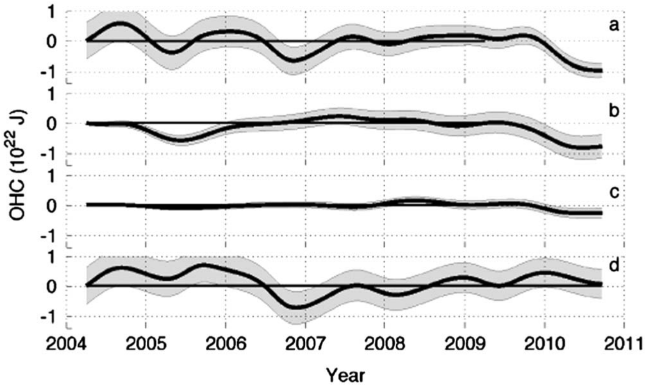

Figure 3. (a) Time series of observed relative heat content above the 4°C isotherm determined from the EN3 v2a Argo data set 6 month low-pass filtered. Uncertainties for OHC above the 4°C isotherm are approximated by the uncertainty in OHC above 2000 m. (b) Integrated ocean heat transport divergence between 26.5°N and 41°N. (c) Integrated ocean-atmosphere surface flux from ERA-interim reanalysis. (d) OHC budget residual (Figures 3a − (3b + 3c)). OHC 10^{22}J.

fluxes of -19.4 W m^{-2} An imbalance of 56.4 Wm^{-2} between MHT and air-sea fluxes would imply a net OHC change of ~12×10^{22} J, which is not observed in Figure 3a. Analysis of this time-mean discrepancy is beyond the goals of this study. However, our analysis is not sensitive to the choice of atmospheric reanalysis as anomalies in ERA-interim and NCEP [*Kalnay et al*., 1996] air-sea heat flux anomalies agree closely, despite a mean difference of -17 W m^{-2}. This is evidence that air-sea heat flux anomalies are likely better constrained than climatological values (section S9). Errors in the climatological values for ocean MHT divergence or atmospheric fluxes would result in spurious linear trends after the time integration of anomalies (section S2). We are seeking to explain interannual anomalies in subtropical OHC and not trends, and the integrated ocean MHT divergence and atmospheric fluxes are defined to have zero mean for the reference period 2004–2009 (Figures 3b and 3c). Extending the reference period to the end of the MHT time series by definition results in no net change in OHC due to the integrated MHT divergence and atmospheric fluxes but forces a significant trend in OHC throughout the time series (section S2). Since within errors no trends are observed in subtropical OHC during the reference period (Figure 3a), we conclude that the mean fluxes are nearly balanced and that our assumption of zero net heat divergence for the reference period 2004–2009 is justified.

6. Discussion and Conclusions

[13] Previous studies argue that, in the midlatitudes, the ocean plays a largely passive role in the generation of upper ocean temperature anomalies on short (monthly-to-interannual) timescales [*Frankignoul*, 1985]. In this paradigm, temperature anomalies in the surface mixed layer are generated by the integrated ocean response to stochastic atmospheric forcing of surface fluxes combined with stabilizing negative feedbacks that act to dampen anomalies on timescales of ~ 6 months. In certain regions of the ocean (including the midlatitude North Atlantic), it has also been shown that thermal anomalies in the winter mixed layer can persist below the seasonal thermocline and "reemerge" the following year as the mixed layer deepens [*Alexander and Deser*, 1995; *Hanawa and Sugimoto*, 2004]. Other studies have suggested that ocean dynamics could play a more active role, with changes in the atmosphere leading to ocean MHT anomalies and ocean-atmosphere feedbacks [*Marshall et al*., 2001].

[14] To examine the processes responsible for OHC changes in the seasonal mixed layer, we define relative heat content change (RHC) following [*Palmer and Haines*, 2009] (section S10), partitioning OHC anomalies into contributions from changes in the mean temperature above the 14°C isotherm ($\mathrm{RHC_T}$) and changes in the volume of water above the 14°C isotherm ($\mathrm{RHC_V}$). The advantage of this approach is the ability to separate air-sea heat flux driven changes ($\mathrm{RHC_T}$) from those arising from changes in ocean circulation ($\mathrm{RHC_V}$).

[15] The separation into volume and temperature relative OHC contributions presented by *Palmer and Haines* [2009] is supported here by the close agreement between $\mathrm{RHC_T}$ above 14°C and the time integrated ERA-interim air-sea fluxes (Figure 4c). During the winter months of 2009/2010 and 2010/2011, the mean winter mixed layer depth corresponded to the average depth of the 18°C isotherm (~200 m), but in 5% of the subtropical gyre, minimum mixed layer temperatures were as cold as 14 °C (Figure 1b). The overall agreement between the surface fluxes and $\mathrm{RHC_T}$ is consistent with our observation that the winter mixed layer depth, and thus the influence of air-sea fluxes, is largely contained above the 14°C isotherm.

[16] $\mathrm{RHC_v}$ above the 14°C isotherm declines throughout 2010, suggesting a reduction in volume due to reduced convergence in this layer. The total RHC change above

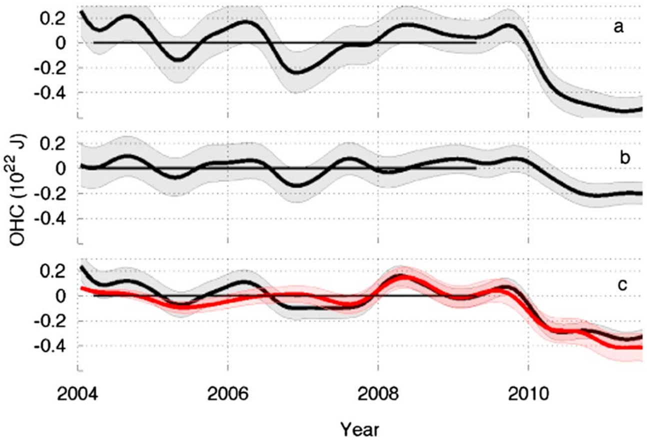

Figure 4. (a) Relative heat content change RHC warmer than the 14°C isotherm. (b) Heat content change due to volume changes $\mathrm{RHC_V}$. (c) Heat content change due to temperature changes $\mathrm{RHC_T}$ and integrated surface heat fluxes from ERA-interim (red). $\mathrm{RHC} = \mathrm{RHC_V} + \mathrm{RHC_T}$. OHC 10^{22}J. RHC uncertainties (grey) are generated by model-based estimates associated with changes in sampling density and locations. For RHC warmer than 14°C, the RHC error is approximated by the $\mathrm{OHC_U}$ uncertainty shallower than 500 m (section S3). The total fractional uncertainties in $\mathrm{RHC_V}$ and $\mathrm{RHC_T}$ are 0.83 $\mathrm{OHC_U}$ and 0.55 $\mathrm{OHC_U}$ according to *Palmer and Brohan* [2011]. The uncertainties are for 10 day values.

14°C declines by -0.5×10^{22} J throughout 2010 and 2011 (Figure 4a), of which $RHC_T = -0.3 \times 10^{22}$ J is due to changes in the average temperature (Figure 4c) and $RHC_V = -0.2 \times 10^{22}$ J due to changes in the volume (Figure 4b): a 60:40 split in heat content changes due to air-sea fluxes and circulation changes, respectively.

[17] The winter (DJF) of 2009/2010 and December 2010 were both characterized by extremely negative phases of the North Atlantic Oscillation. Modeling studies using seasonal forecast systems have suggested that the negative North Atlantic Oscillation (NAO) during winter 2009/2010 was driven by dynamic processes internal to the atmosphere [*Fereday et al.*, 2012; *Jung et al.*, 2011]. In contrast, it has been suggested that the return to a negative NAO phase during December 2010 may have been driven by the reemergence of existing subsurface temperature anomalies in the North Atlantic [*Taws et al.*, 2011]. *Maidens et al.*, [2013] demonstrate that anomalous OHC and associated sea surface temperature anomalies in the North Atlantic are indeed responsible for successful forecasts of the negative NAO state in December 2010. This hypothesis is consistent with modeling and observational studies that have suggested predictability of the NAO based on knowledge of preceding Atlantic sea surface temperature (SST) anomalies [*Cassou et al.*, 2007; *Rodwell et al.*, 1999].

[18] Our 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. Building on earlier work linking subsurface temperature anomalies and predictability of the NAO [*Cassou et al.*, 2007], these results suggest that the ocean MHT may be active in the events leading to the extreme negative phase of the NAO during December 2010.

[19] Observations show that there has been an abrupt and sustained cooling in the upper 2 km of the subtropical Atlantic between 2010 and 2012. The associated reduction in OHC is partitioned equally between the seasonally active mixed layer and the deeper ocean (below the 14 °C isotherm). We find that a reduction of the AMOC at 26.5°N is the largest contributor to the observed cooling in subtropical Atlantic. In the seasonally mixed layer, temperature anomalies are a result of both heat loss to the atmosphere and reduced MHT associated with a reduction in the AMOC. Our results emphasize the role for the ocean in the North Atlantic climate system on seasonal-to-interannual timescales and suggest a role for the AMOC in setting subsurface temperature anomalies that have previously been linked to reemerging SST patterns and subsequent anomalies in the NAO [*Taws et al.*, 2011] and predictability of December 2010 NAO negative state [*Maidens et al.*, 2013]. Finally, ~50 % of the observed OHC anomaly is outside the influence of the surface mixed layer and essentially isolated from the atmosphere on seasonal timescales. We speculate that these temperature anomalies may become climatically relevant on longer (e.g., decadal) timescales.

[20] **Acknowledgments.** Stuart Cunningham is supported by the Scottish Funding Council through the Marine Alliance for Science and Technology Scotland program and by the European Commission in the 7th Framework Programme for Research through the NACLIM project (grant agreement 308299). Chris Roberts and Matthew Palmer are supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101). Data from the RAPID-MOC/MOCHA array are funded by the Natural Environment Research Council (NERC) and National Science Foundation (NSF), and are freely available from http://www.rapid.ac.uk/rapidmoc. Florida Current transport estimates are funded by the National Oceanic and Atmospheric Administration (NOAA), and are available from http://www.aoml.noaa.gov/phod/floridacurrent.

[21] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Alexander, M., and C. Deser (1995), A mechanism for the recurrence of wintertime midlatitude SST anomalies, *J. Phys. Oceanogr.*, *25*(1), 122–137.

Baringer, M. O., and J. C. Larsen (2001), Sixteen years of Florida current transport at 27°N, *Geophys. Res. Lett.*, *26*(16), 3179–3182.

Bryden, H. L., and S. Imawaki (2001), Ocean heat transport, in *Ocean Circulation & Climate: Observing and Modelling the Global Ocean*, edited by G. Siedler, J. Church, and J. Gould, p. 715, Academic Press, San Diego, San Francisco, New York, Boston, London, Sydney, Tokyo.

Cassou, C., C. Deser, and M. A. Alexander (2007), Investigating the impact of reemerging sea surface temperature anomalies on the winter atmospheric circulation over the North Atlantic, *J. Clim.*, *20*(14), 3510–3526.

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

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*(656), 553–597.

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*, 661–676.

Fereday, D., R. Maidens, A. Arribas, A. A. Scaife, and J. R. Knight (2012), Seasonal forecasts of northern hemisphere winter 2009/10, *Environ. Res. Lett.*, *7*(3), 034,031.

Frankignoul, C. (1985), Sea surface temperature anomalies, *Rev. Geophys.*, *23*(4), 357–390.

Hanawa, K., and S. Sugimoto (2004), 'Reemergence' areas of winter sea surface temperature anomalies in the world's oceans, *Geophys. Res. Lett.*, *31*, L10303, doi:10.1029/2004GL019904.

Hobbs, W. R., 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.

Ingleby, B., and M. Huddleston (2007), Quality control of ocean temperature and salinity profiles—Historical and real-time data, *J. Mar. Syst.*, *65*, 158–175.

Jayne, S. R., and J. Marotzke (2001), The dynamics of ocean heat transport variability, *Rev. Geophys.*, *39*(3), 385–411.

Johns, W. E., et al. (2011), Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N, *J. Clim.*, *24*(10), 2429–2449.

Jung, T., F. Vitart, L. Ferrnanti, and J.-J. Morcrette (2011), Origin and predictability of the extreme negative NAO winter of 2009/10, *Geophys. Res. Lett.*, *38*, L07701, doi:10.1029/2011GL046786.

Kalnay, E., et al. (1996), The NCEP/NCAR reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–495.

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.

Kanzow, T., et al. (2010), Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N, *J. Clim.*, *23*(21), doi:10.1175/2010JCLI3389.1171.

Kara, A. B., P. A. Rochford, and B. E. Hurlburt (2000), An optimal definition for ocean mixed layer depth, *J. Geophys. Res.*, *105*(C7), 16,803–816,821.

Knight, J. R. (2005), A signature of persistent natunral thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GLO24233.

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf (2007), On the driving processes of the Atlantic meridional overturning circulation, *Rev. Geophys.*, *45*, RG2001, doi:10.1029/2004RG000166.

Latif, M., E. Roeckner, M. Botzet, M. Esch, H. Haak, S. Hagemann, J. H. Jungclaus, S. Legutke, S. Marsland, and U. Mikolajewicz (2004), Reconstructing, monitoring and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature, *J. Clim.*, *17*(7), 1605–1614.

Maidens, A., A. Arribas, A. Scaife, C. MacLachlan, D. Peterson, and J. R. Knight (2013), The inclence of surface forcings on predition of the North Atlantic Oscillation regime of winter 2010–11, *Mon. Weather Rev.*, doi:10.1175/MWR-D-1113-00033.00031, in press.

Marshall, J., H. Johnson, and J. Goodman (2001), A study of the interaction of the North Atlantic Oscillation with ocean circulation, *J. Clim.*, *14*(7), 1399–1321.

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

Palmer, M. D., and K. Haines (2009), Estimating oceanic heat content change using isotherms, *J. Clim.*, *22*(19), 4953–4969.

Palmer, M. D., and P. Brohan (2011), Estimating sampling uncertainty in fixed-depth and fixed-isotherm estimates of ocean warming, *Int. J. Climatol.*, *31*, 980–986.

Rahmstorf, S., and A. Ganopolski (1999), Long-term global warming scenarios computed with an efficient coupled climate model, *Clim. Change*, *43*(2), 353–367.

Rayner, D., et al. (2011), Monitoring the Atlantic meridional overturning circulation, *Deep Sea Res., Part II*, *58*(17–18), 1744–1753.

Rhines, P., S. Häkkinen, and S. Josey (2008), Is the oceanic heat transport significant in the climate system?, in *Arctic-Subarctic Ocean Fluxes*, edited by R. R. Dickson, J. Meincke, and P. Rhines, pp. 87–109, Springer, Dordrecht, The Netherlands.

Rodwell, M. J., D. P. Rowell, and C. K. Folland (1999), Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature*, *398*(6725), 320–323.

Taws, S. L., R. Marsh, N. C. Wells, and J. Hirschi (2011), Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO, *Geophys. Res. Lett.*, *38*, L20601, doi:10.1029/2011GL048978.

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.