



Supporting Online Material for
**Temporal Variability of the
Atlantic Meridional Overturning Circulation at 26.5°N**

Stuart A. Cunningham,* Torsten Kanzow, Darren Rayner, Molly O. Baringer,
William E. Johns, Jochem Marotzke,* Hannah R. Longworth, Elizabeth M. Grant,
Joël J.-M. Hirschi, Lisa M. Beal, Christopher S. Meinen, Harry L. Bryden

*To whom correspondence should be addressed. E-mail: scu@noc.soton.ac.uk (S.A.C.);
marotzke@dkrz.de (J.M.)

Published 17 August 2007, *Science* **317**, 935 (2007)

DOI: 10.1126/science.1141304

This PDF file includes:

SOM Text
Figs. S1 to S4
References

Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5°N

Stuart A. Cunningham¹, Torsten Kanzow¹, Darren Rayner¹, Molly O. Baringer², William E. Johns³, Jochem Marotzke⁴, Hannah R. Longworth¹, Elizabeth M. Grant¹, Joël J.-M. Hirschi¹, Lisa M. Beal³, Christopher S. Meinen² and Harry L. Bryden¹

¹National Oceanography Centre, Empress Dock, Southampton SO14 3ZH

²NOAA-AOML/PHOD, 4301 Rickenbacker Causeway, Key Biscayne FL 33149

³RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149

⁴Max Planck Institute for Meteorology, Bundesstrasse 5, D-20146 Hamburg

Submitted for publication in *Science* February 2007

Supporting online Material

Rapid Climate Change

Rapid Climate Change (Rapid) is a directed programme of the Natural Environment Research Council (NERC). The project to monitor the Atlantic meridional overturning circulation at 26.5°N reported here is a joint UK/US collaboration between the National Oceanography Centre Southampton UK, the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences and the NOAA Atlantic Oceanographic and Meteorological Laboratory Miami USA. This joint effort is known as RAPID-MOC/MOCHA where MOCHA stands for Meridional Circulation and Heat Flux Array. The website for RAPID-MOC/MOCHA is <http://www.noc.soton.ac.uk/rapidmoc/>.

Methods

The 26.5°N Atlantic section naturally separates into a western boundary region where the Gulf Stream flows through the narrow (80 km), shallow (800 m) Florida Straits between Florida and the Bahamas and a mid-ocean region spanning the Atlantic from the Bahamas at about 77°W to Africa at about 15°W (Fig. S1). The variability in Gulf Stream flow is derived from cable voltage measurements across Florida Straits at 27°N between Florida and the Bahamas (Website 1) and calibrated with regular velocity sections across Florida Straits (1). A gap in the time series of approximately two months from 4th September to 28th October 2004 is due to hurricane Frances that destroyed the facility recording the voltage. Here linear interpolation is chosen to fill the gap. The variability in wind-driven surface layer Ekman transport across the 26.5°N transatlantic section is derived from QuikScat satellite-based wind observations (Website 2). To monitor the mid-ocean flow, we deployed an array of moored instruments along the 26.5°N

transatlantic section as part of the Rapid project (Fig. S2). Because of the nature of geostrophic flow, we can quantify the variability in zonally integrated meridional flow in a rectangular ocean section by monitoring the vertical profiles of temperature and salinity and hence density at the western and eastern ends of the section. The 26.5°N section does not have vertical side walls or a flat bottom but the Rapid array places moorings up the boundary slopes to fill in side-wall triangles in the way traditional hydrographic sections (2) include shallower stations up the slope. Here we concentrate on the variability in the difference between the western and eastern boundary density profiles that define the section-average geostrophic velocity profile. Above 2500 m depth which is the minimum depth of the Mid Atlantic Ridge at 26.5°N, this profile based on end-point measurements represents the geostrophic velocity profile relative to the velocity at 2500 m depth. Below 2500 m depth, there may be mean pressure gradients across the Mid Atlantic Ridge but for the first year's measurements the pressure gradient fluctuations across the Ridge have only a small effect on the basin-scale variability (3). Hence, to define the baroclinic variability we assume that the difference in end-point density profiles represents the deep basin-scale geostrophic flow as well. Thus we will examine the variability in the baroclinic structure of the mid-ocean geostrophic velocity based on the first year's end-point profiles from the Rapid array at 26.5°N.

We deployed the mid-ocean array during February-March 2004 and recovered it in March-May 2005 (4, 5). The overlapping period when the entire array was working for its first year was 28 March 2004 to 31 March 2005. We have since maintained the array through 2005, 2006 and 2007 with refurbishments of the western boundary array in spring and the eastern boundary and mid-Atlantic Ridge arrays in autumn. Here we present results from the first year. The design of the Rapid array for monitoring basin-scale circulation was tested in numerical ocean circulation models (6, 7) and a companion paper (3) demonstrates from the first year's time series that four independently measured transports (Gulf Stream, Ekman, internal mode baroclinic geostrophic and external mode barotropic geostrophic transports) are in overall mass balance for time scales longer than 10 days, providing evidence that the monitoring system works.

The basic principle of the array is to make time series measurements of temperature and salinity throughout the water column at the eastern and western boundaries of the Atlantic 26.5°N section to estimate the zonally integrated geostrophic profile of northward velocity on a daily basis. On the western side, we join profiles from WBH2, WBH1 and WB2 (Fig. S3) to construct a single profile of dynamic height at daily intervals from 29 March 2004 to 31 March 2005. Temperature, conductivity and pressure time series at fixed depths are processed and filtered to remove fluctuations with periods shorter than one day and interpolated to 20 dbar levels (3). Dynamic height is then calculated relative to zero at the bottom. Practically speaking, WBH2

provides the dynamic height profile from the bottom at 4820 dbar up to 4300 dbar; WBH1 provides the dynamic height profile from 4300 up to 3800 dbar using the dynamic height value from WBH2 at 4300 dbar at each time; and WB2 provides the dynamic height profile from 3800 dbar up to 120 dbar, in turn using the dynamic height value from WBH1 at 3800 dbar at each time. Similarly, the dynamic height profiles from moorings EB1, EBH1 EBH2, EBH3, EBH4 and EBH5 (Fig. S3) are joined to construct a single profile of dynamic height for the eastern boundary at daily intervals from the bottom at 4920 dbar up to the top of EBH5 at 540 dbar.

Mid-Ocean Baroclinic Variability

To examine the variability in mid-ocean baroclinic structure, we calculate the profile of daily dynamic height anomaly from the mean profile at the eastern and at the western sides and then take the difference, east - west, of the anomaly profiles. For the mean profile, the dynamic height on the west above 120 dbar and on the east above 540 dbar, are taken to match the average profiles from historical hydrographic stations (8). At the western side, we linearly extrapolate the western anomaly upwards from 120 dbar to the surface using the anomaly at 240 dbar to estimate the gradient. At the eastern side, we linearly extrapolate the anomaly up to 240 dbar using the anomalies at 840 and 540 dbars to estimate the gradient and then carry the anomaly at 240 dbar at constant value up to the surface. Variability at the eastern boundary is an order of magnitude less than that at the west (8), so experiments with different extrapolation techniques above 540 dbar did not greatly modify the results. The time-averaged dynamic height difference (east - west) shows the vertical structure of the meridional geostrophic transport per unit depth (Fig. 1). Comparison with historical hydrographic stations, i.e., subsampling the stations to match the vertical distribution of moored instruments, suggests that the error in layer transports derived from the array is 0.8 Sv for 0-800m and 2.0 Sv for transport below 3000 m in the west and 0.9 Sv for 0-800m in the east (there is very little variability in deep water transport on the east in the hydrographic stations). For the first year of measurements density profiles do not extend into Antarctic Bottom Water, deeper than 5000 m. The mean northward AABW flux from five hydrographic sections is 2.1 Sv deeper than 5000 m (9). Compensation of this unmeasured flux potentially adds 0.4 Sv to the estimate of the maximum overturning.

Direct Velocity Measurements of the Shallow and Deep Western Boundary Currents

West (inshore) of WB2, we use velocity measurements on WB2, WB1, WB0 and WBA to define the wedge transport between WB2 and the Bahamas. Because this wedge transport includes part of the Antilles Current above 800 m depth, the Rapid array was designed to monitor it with direct velocity measurements. The time-averaged wedge transport of 1.8 Sv is made up of 2.4 Sv above 800 m depth, -0.2 Sv between 800 and 1100 m, and -0.4 Sv between 1100 and 3000 m. A depth-independent transport adjustment for each daily mid-ocean geostrophic profile from the dynamic height difference (mean plus daily anomaly) is set by forcing the mid-ocean geostrophic transport to balance the wedge plus Gulf Stream plus Ekman transport on a daily basis. In a companion paper (3), we demonstrate that such mass compensation does occur on time scales longer than about 10 days, that is the Gulf Stream plus Ekman transport is anti-correlated with the mid-ocean geostrophic transport including the wedge transport on time scales longer than 10 days.

Calculating the maximum meridional overturning

In order to calculate a maximum overturning, as commonly used by modellers in their analysis of the overturning (6), the upper mid-ocean transport is computed in a way that minimises the amount of southward transport, thus maximising the overall amount of northward transport of upper waters when Florida Straits, Ekman and mid-ocean transports are added together. The mid-ocean flow is generally southward from the surface to about 800 m depth, but between about 800 m and 1100 m depth there is a region of northward flow, while below about 1100 m depth the deep flow is generally southward. To obtain the minimum value of southward upper mid-ocean transport on each day, we find the depth above which there is intermediate northward flow and below which there is southward flow. The mean depth of this zero-crossing over the year is 1041 m with a standard deviation of 92 m. The upper mid-ocean transport is then defined to be the transport from the surface down to this depth on each day. On nine days there is no northward flowing intermediate water and the mid-ocean transport is summed down to only 800 m because this is the approximate depth of the Florida Straits, where northward flowing Gulf Stream waters extend to the bottom. For the first year of measurements density profiles do not extend into Antarctic Bottom Water, deeper than 5000 m. The mean northward AABW flux from five hydrographic sections is 2.1 Sv deeper than 5000 m (9). Compensation of this unmeasured flux potentially adds 0.4 Sv to the estimate of the maximum overturning.

Time scales of variability

To estimate the time scales of the variability, we calculated autocorrelation functions for the upper mid-ocean, overturning and LNADW transports. The zero-crossing for both the upper mid-ocean and overturning transports is at 45 day time lag, while for the deep water transport the zero-crossing is at 24 days. Integrating the autocorrelation function out to the zero-crossing yields integral time scales of 23.6, 24.3 and 12.7 days for upper mid-ocean recirculation, overturning and LNADW transports respectively. We estimate there are about 15, 15 and 29 independent values in the year-long time series for upper mid-ocean recirculation, overturning and LNADW transports respectively.

Figure Captions

Figure S1. 26.5°N section across the subtropical North Atlantic Ocean. The red section from Bahamas to Africa represents the track of the 2004 section whose temperature distribution is shown below. Magenta bars below denote the positions of the 2004-05 Rapid moorings.

Figure S2. Schematic of 26.5°N mooring array during its 2004-2005 deployment. The array comprises 3 sub-arrays: the Western Boundary with 7 moorings, the Mid-Atlantic Ridge with 4 moorings (2 on either side of the Ridge), and the Eastern Boundary with 8 moorings. Moorings are not drawn to scale but represent the nominal instrument depths and buoyancy distribution. Most moorings were deployed with Bottom Pressure Recorders (BPR) equipped with drop off mechanism to decouple the BPR measurements from mooring motion. Two moorings were designed with a McLane Moored Profiler to travel up and down the length of the mooring taking conductivity, temperature, pressure and current measurements.

Figure S3. Moorings near the a) western and b) eastern boundaries of the 26.5°N section that are used to construct the western and eastern dynamic height profiles. Instrument records on WB2, WBH2 and WBH1 in the west and on EB1, EBH1, EBH2, EBH3, EBH4 and EBH5 in the east provide the dynamic height profiles at the boundaries. In the west, moorings WBA, WB0, WB1 and WB2 made velocity measurements that define the wedge transport. Note the difference in zonal scale for the western and eastern boundary regions.

Figure S4. Contoured time series of temperature as a function of depth for instruments on mooring WB2 (Fig. S2). Note the extreme event in the beginning of November when temperature contours below 3°C descend sharply by more than 700 m indicating the disappearance of LNADW and creating the anomalous velocity profile shown in Fig. 1.

References and Notes

1. M. O. Baringer, J. C. Larsen, *Geophys. Res. Lett.*, **28**, 3179 (2001).
 2. M. H. Hall, H. L. Bryden, *Deep Sea Res.*, **29**, 339 (1982).
 3. T. Kanzow et al., *Science*, submitted February 2007.
 4. D. Rayner, et al., " RRS Discovery Cruises D277/D278, RAPID mooring cruise report, February - March 2004", Southampton Oceanography Centre Cruise Report No. 53, 103p. (2005).
 5. S. A. Cunningham et al., " RAPID Mooring cruise report April - May 2005, RRS *Charles Darwin* Cruise CD170 and *RV Knorr* Cruise KN182-2, April - May 2005", National Oceanography Centre Southampton Cruise Report 2, Southampton, UK, 147 p. (2005).
 6. J. Hirschi et al., *Geophys. Res. Lett.*, **30** (7), 1443.doi:10.1029/2002GL016776.
 7. J. Baehr, J. Hirschi, J.-O Beismann, J. Marotzke, *J. Mar. Res.*, **62**, 283 (2004).
 8. H. R. Longworth, " Constraining variability of the Atlantic meridional overturning circulation at 26.5°N from historical observations", Ph.D. Thesis, University of Southampton, 198p. (2007).
 9. H. L. Bryden, H. R. Longworth, S. A. Cunningham, *Nature*, **438**, 655 (2005).
- Website 1. 2006. www.aoml.noaa.gov/phod/floridacurrent
- Website 2. 2006. <http://winds.jpl.nasa.gov/missions/quikscat/index.cfm>

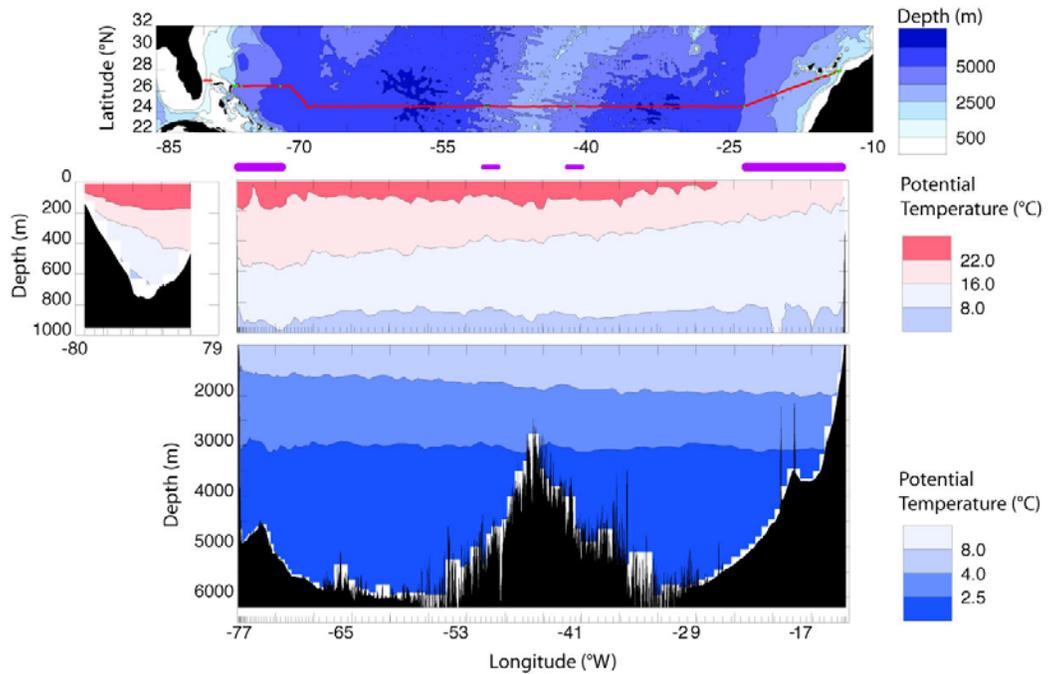


Figure S1. 26.5°N section across the subtropical North Atlantic Ocean. The red section from Bahamas to Africa represents the track of the 2004 hydrographic section whose temperature distribution is shown below. Magenta bars below. denote the positions of the 2004-2005 Rapid moorings.

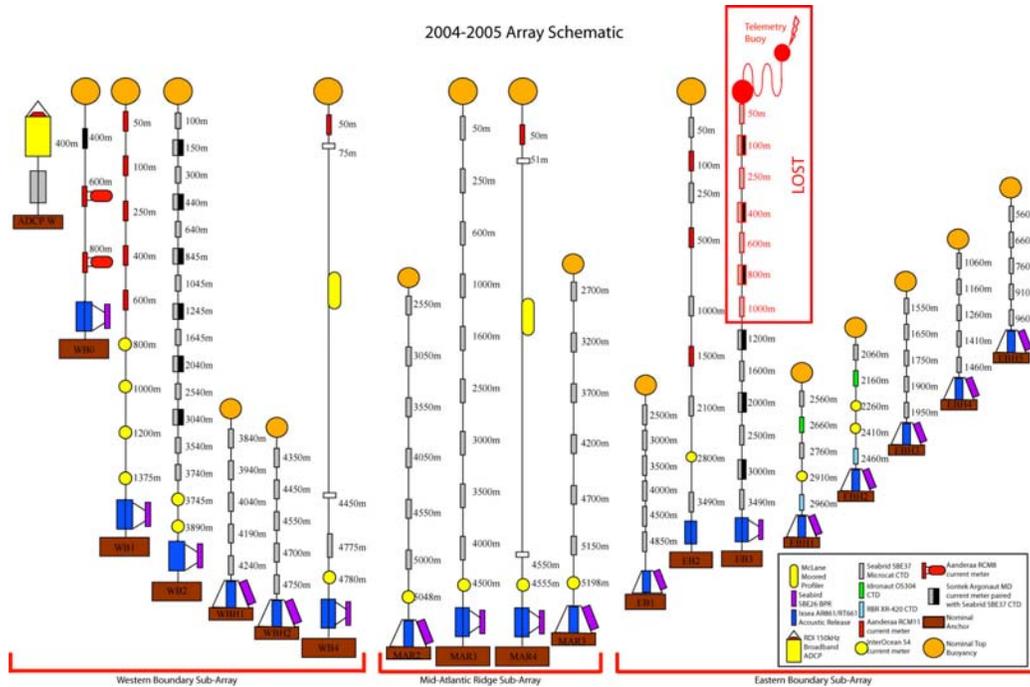


Figure S2. Schematic of 26.5°N mooring array during its 2004-2005 deployment. The array comprises 3 sub-arrays: the Western Boundary with 7 moorings, the Mid-Atlantic Ridge with 4 moorings (2 on either side of the Ridge), and the Eastern Boundary with 8 moorings. Moorings are not drawn to scale but represent the nominal instrument depths and buoyancy distribution. Most moorings were deployed with Bottom Pressure Recorders (BPR) equipped with drop off mechanism to decouple the BPR measurements from mooring motion. Two moorings were designed with a McLane Moored Profiler to travel up and down the length of the mooring taking conductivity, temperature, pressure and current measurements.

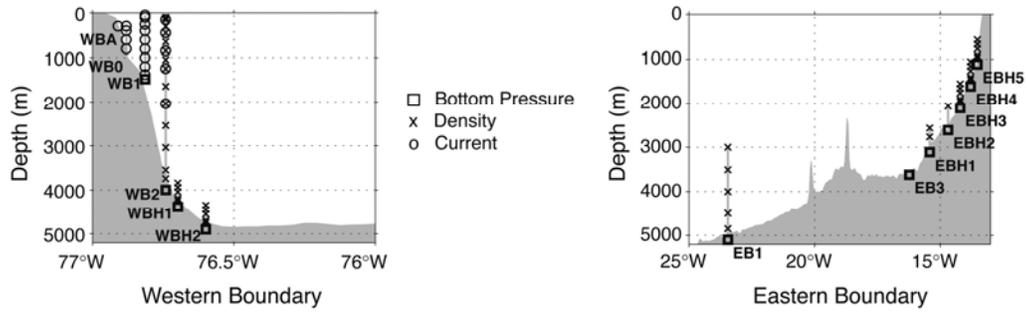


Figure S3. Moorings near the a) western and b) eastern boundaries of the 26.5°N section that are used to construct the western and eastern dynamic height profiles. Instrument records on WB2, WBH2 and WBH1 in the west and on EB1, EBH1, EBH2, EBH3, EBH4 and EBH5 in the east provide the dynamic height profiles at the boundaries. In the west, moorings WBA, WB0, WB1 and WB2 made velocity measurements that define the wedge transport. Note the difference in zonal scale for the western and eastern boundary regions.

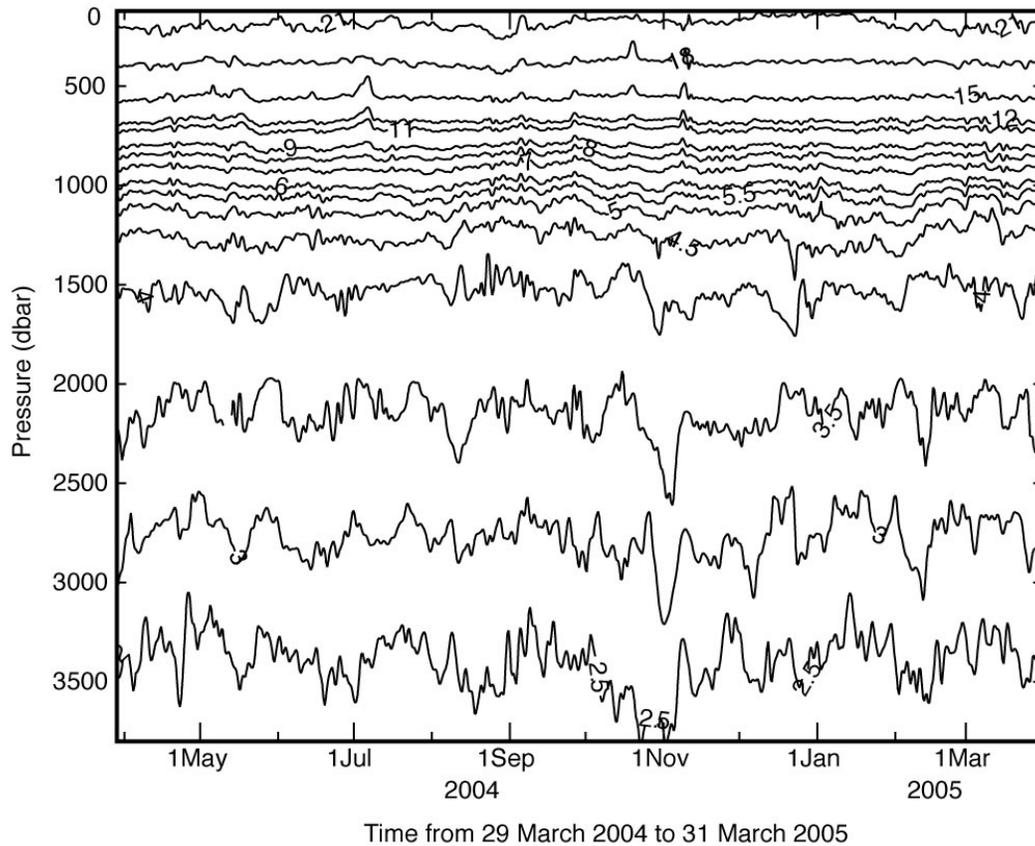


Figure S4. Contoured time series of temperature as a function of depth for instruments on mooring WB2 (Fig. S2). Note the extreme event in the beginning of November when temperature contours below 3°C descend sharply by more than 700 m indicating the disappearance of LNADW and creating the anomalous velocity profile shown in Fig. 1.