Western Boundary Time Series in the Atlantic Ocean

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1. Project Summary

Goal/Rationale: This project seeks to continuously monitor two important components of the thermohaline circulation in the Subtropical North Atlantic with the ultimate goal of determining the state of the overturning circulation and providing a monitoring system for rapid climate change. The components include the northward flowing Florida Current and the southward flowing Deep Western Boundary Current. The Florida Current is the warm surface intensified flow that represents the bulk of what we call the upper limb of the thermohaline circulation in the subtropical Atlantic.

The Western Boundary Time Series project represents NOAA's longest term observing system for the Atlantic Meridional Overturning Circulation (MOC). Over the past 25+ years the program has worked to measure both the warm upper and cold lower limbs of the MOC near the western boundary of the Atlantic Ocean at 27°N.

Components of the observing system include continuous real-time cable measurements of Gulf Stream transport, cable calibration cruises including eight to ten small boat dropsonde cruises, quarterly Walton Smith CTD/LADCP cruises, annual full depth hydrographic CTD/LADCP cruises across the Deep Western Boundary Current and beginning in 2004 continuous moored measurements of the deep transports using inverted echosounders (PIES).

General Overview:
The project maintains NOAA's well-established and climatically significant Florida Current volume transport time series. Daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-use cables spanning the Straits of Florida since 1982. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory. These transport measurements contain interannual and decadal changes on the

order of 10% of the long-term mean transport, and during some periods the decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation during some time periods, and by extension with the large-scale sea-surface temperature patterns associated with the North Atlantic Oscillation, suggests connections to tropical Atlantic variability on climatically significant time scales. These strong correlations also link the Florida Current transport with the numerous significant weather and climate phenomena that are related through large-scale ocean-atmosphere patterns in the Atlantic, including decadal and inter-decadal variations in fisheries, rainfall, and hurricane activity.

The repeated hydrographic and tracer sampling at Abaco has established a high-resolution, high quality record of water mass properties in the Deep Western Boundary Current at 26.5ºN. Events such as the intense convection period in the Labrador Sea and the renewal of classical Labrador Sea Water in the 1980s are clearly reflected in the cooling and freshening of the Deep Western Boundary Current waters off Abaco with the arrival of a strong chlorofluorocarbon pulse approximately 10 years later. This data set is unique in that it is not a single time series site but in instead a time series of transport sections, including high quality water property measurements, of which very few are available in the ocean that approach even one decade in length. This element includes annual cruises across the DWBC to measure the water mass properties and transports. With the cooperation of University of Miami researchers (Drs. Johns and Beal) and funding from the National Science Foundation for the Meridional Overturning Circulation and Heat transport Array (MOCHA), and sharing of personnel and ship-time resources, these cruises have been conducted twice each year since 2004. This level of sampling will continue through 2014.

The Western Boundary Time Series project consists of two main elements, each of which is broken into several sub-elements:

Continuous Measurements: –

- Antilles and Deep Western Boundary Current transport time-series variability is monitored using a line of five PIES/CPIES moorings.
- Florida Current transport time series using pressure tide gauges placed into service in July 2008.
- Florida Current transport time-series variability is monitored using an out-of-service phone cable instrumented with a voltage recording system. In addition a backup system for the current cable is being tested: this system includes two pressure gauges spanning the Florida Straits at 27°N.

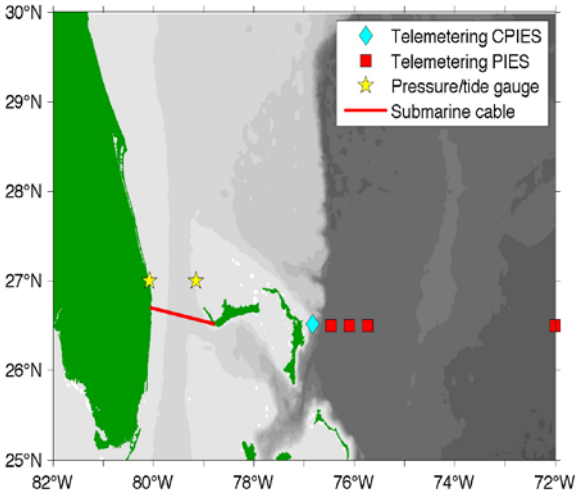


Figure 1: *Summary locations of continuous time series components of the Western Boundary Time Series program.*

Discrete Property Measurements –

- Antilles and Deep Western Boundary Current transport and water mass snapshot variability are monitored by annual CTD/LADCP cruises for velocity, temperature, salinity and oxygen. These measurements are used to describe long term watermass changes in the circulation in addition to calibration of the continuous time series measurements.
- Florida Current transport snapshot variability and the calibration and continuity of the cable system are monitored using:
    - dropsonde/XBT cruises up to 10 times per year (this data is also used by the SOOP program for analysis of the data from the AX7 line) along the 27N latitude in the Florida Straits.
    - CTD/LADCP sections conducted on small boats four times per year along the 27N latitude in the Florida Straits each year, providing additional samples for cable calibration as well detailed vertical structure of the Florida Current velocity coincident with temperature, salinity and oxygen measurements and hence can provide estimates of property fluxes beyond just volume transport.

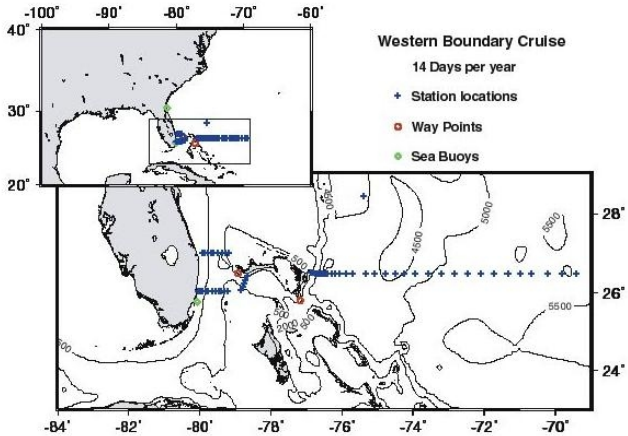


Figure 2: *Summary locations of discrete CTD/LADCP and dropsonde locations from the Western Boundary Time series program.*

The observations carried out at NOAA/AOML as part of the Western Boundary Time Series project also couple constructively with the US/NSF & UK/NERC funded moored time series observations east of Abaco Island, Grand Bahamas to serve three primary purposes for climate variability studies:

1. Monitoring of the DWBC for water-mass and transport signatures related to changes in the strengths and regions of high latitude water mass formation in the North Atlantic.
2. Providing the western boundary endpoint of a subtropical Meridional Overturning Circulation and heat transport monitoring array designed to measure the thermohaline overturning circulation at 26.5 N and the time varying meridional heat transport.
3. Monitoring the intensity of the Florida Current and the Antilles current as an index of interannual variability in the strength of the subtropical gyre.

The Western Boundary Time Series project is one component of the NOAA "Ocean Reference Station" system in the Atlantic Ocean, and it specifically addresses the NOAA climate goals by providing long term integrated measures of the global thermohaline

(overturning) circulation. This project is designed to deliver yearly estimates of the state of the thermohaline circulation, i.e. its intensity, properties, and heat transport. Heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Monitoring the transport within the ocean is a central element of documenting the overturning circulation of fresh water, heat and carbon uptake and release. Long-term monitoring of key choke points, such as the boundary currents along the continents including the Gulf Stream and the Deep Western Boundary Current, will provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the bulk of the Meridional Overturning Circulation.

Primary users of the data collected in this program are largely the international scientific community, of which some small indicator of its impact includes the more than 25 research scientists from more than 16 different institutions and 6 countries that have subscribed to the real-time email update distribution list. This is only a small subset of the research community that uses this data that has been endorsed by many national and international science panels including US CLIVAR, International CLIVAR, OceanSites, OceanObs09 etc. While direct assimilation of transport information into operational models is not routinely possible, modeling and analysis products regularly make use of these data as benchmarks for model fidelity. Due to the longstanding nature of this program, a large international program was started in 2004 in collaboration with the U.S. National Science Foundation, the U.K. Rapid Watch Program and Germany to measure the remaining components of the MOC circulation not included in NOAA's long-standing program.

2. Scientific and Observing System Accomplishments

Observing system accomplishments

- *Florida Current Cable Time Series:*
  The cable transport recording instruments are located at Eight Mile Rock, Grand Bahamas Island. At Eight Mile Rock and in West Palm Beach, Florida, electrode equipment is in place, securing a stable reference voltage (i.e. grounds) at either end of the submerged telephone cable. The monitored cable can be seen in Figure 1, stretching across the Florida Straits.

  Data acquisition has continued using the cable during fiscal year 2011; during this FY there were no data losses from the voltage recording system, highlighting the continued success of the stable system of processing and quality control for both the calibration section data and the cable transport data implemented in FY05. Cable voltages are recorded every

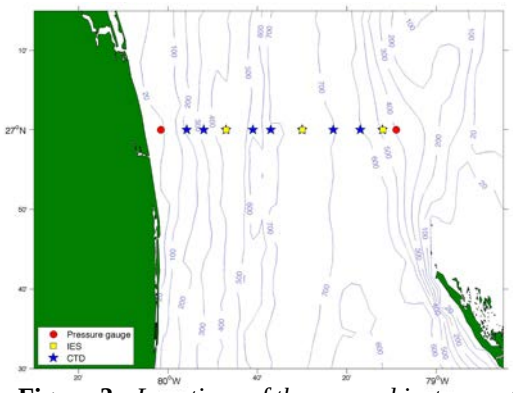


Figure 3: *Locations of the moored instruments being tested as possible backup systems for measuring the Florida Current transport. Also shown are the locations of the standard CTD/LADCP and dropsonde/XBT sites used in the Florida Straits.*

minute, and are post processed to form each daily transport estimate.

- *Florida Current pressure gauge time series:* Utilizing both AOML Base funds and OCO funds, in July 2008 a set of moored instruments was deployed to test combinations of different of equipment that could be used to monitor the transport of the Florida Current continuously in case of a future failure of the real-time cable system. Two new pressure gauges were deployed in shallow water at the edges of the Straits while two 1980s-era IES moorings, and one 1980s-era PIES mooring were deployed (Figure 3). These instruments were recovered for the first time in June 2009 – one IES mooring failed to respond and is believed to be flooded and lost. The pressure gauges were downloaded and redeployed with fresh batteries, while the remaining IES and PIES moorings were returned to the lab for data download. This data will be evaluated to determine whether this combination of instruments can reproduce the measurements made via the cable. In place since July 2008 remain the two pressure gauges.

- *Florida Current Discrete Measurements:* In addition to the cable measurements, regular calibration cruises are required for this project's success that include four 2-3 day small charter boat calibration cruises on the R/V F. G. WALTON SMITH each year and 10 one-day charters onboard small fishing vessels, provided sufficient ship-time is available. The number of cruises conducted has been less than desired due to a combination of factors including increasing charter costs, decreasing charter funding, inclement weather, instrument failure and the general difficulty in obtaining small boat charters.

  A total of six 1-day surveys were conducted using a dropsonde profiler during FY11. The economy has reduced the availability of charter vessels and those vessels still in service are overbooked and do not want to take on the additional risk of vessel wear and tear from crossing the Straits of weather in anything sea-state with larger than 2 foot waves. Measurements are taken at nine stations along 27ºN (same locations as the CTD sites shown in Figure 3) and include vertically averaged horizontal velocity, surface velocity and expendable temperature probes (XBTs). The cruise dates are shown in Table 1.

Planned Cruise	FY 2011	FY 2010	FY 2009	FY 2008	FY 2007
1	17-Dec-10	10-Dec-09	2-Oct-08	4-Oct-07	13-Dec-06
2	16-Mar-11	24-Mar-10	9-Oct-08	6-Nov-07	15-Dec-06
3	27-May-11	3-Jun-10	5-Dec-08	28-Nov-07	29-Mar-07
4	23-Jun-11	16-Jun-2010 dropsonde electronics problems	30-Dec-2008 section failed due to poor weather	7-Dec-07	19-Jun-07
5	16-Sep-11	7/28/2010 dropsonde lost	13-Feb-09	23-Jan-08	10-Jul-07
6	28-Sep-11	5-Aug-2010 dropsonde electronics problems	17-Mar-09	29-Jan-08	5-Sep-2007, dropsonde electronics problems

7		13-Aug-10	12-Jun-09	22-Apr-08	27-Sep-07
8		23-Aug-10	15-Jul-09	7-May-08	Postponed to FY08 due to weather
9		10-Sep-10	10-Sep-09	10-Jul-2008 dropsonde lost	

Table 1: *Cruise dates for 1-day small boat calibration cruises using dropsonde instrument.*

Two-to-three day cruises on RV Walton Smith are generally scheduled four times per year. Sufficient ship-time funds for all four cruises were provided by the charter ship fund in FY11. All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figures 2 and 3. Table 2 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

FY2011		FY2010		FY2009		FY2008	
Date	Samples	Date	Samples	Date	Samples	Date	Samples
Nov 30-Dec 1, 2010	60 O2, 48 S	Nov 23-24, 2009	60 O2, 48 S	Dec 11-12, 2008	60 O2, 48 S	Dec 19-20, 2007	60 O2, 48 S
Mar 8-9 2011	60 O2, 48 S	Feb 25-26, 2010	60 O2, 48 S	Feb 23-24, 2009	60 O2, 48 S	Jul 7-9, 2007	60 O2, 48 S
Jun 14-15, 2011	60 O2, 48 S	May 18-20, 2010	60 O2, 48 S	Jun 15-17, 2009	60 O2, 48 S		
Sep 20-21, 2011	60 O2, 48 S	Aug 23-24, 2010	60 O2, 48 S	Sep 10-11, 2009	60 O2, 48 S		
100% of planned cruises		100% of planned cruises		100% of planned cruises		50% of planned cruises	

Table 2: *Cruise dates for 2-3 day calibration cruises on the R/V Walton Smith. Note FY2008 Only one two-day cruise was planned in FY2008 due to lack of ship-time charter funds; a second three-day cruise was done using sea-days donated by a related program at U. Miami.*

- *Deep Western Boundary Current Measurements:*

Since 2004, the WBTS has produced daily time-series of the magnitude of the Deep Western Boundary Current mass transport in quasi-real-time (downloaded to research ships twice each year). This monitoring system includes a moored array of Inverted Echo Sounders (IESs), and each instrument is additionally equipped with a bottom pressure gauge (PIES) and in one case a bottom current meter (CPIES). The line of PIES/CPIES moorings stretches across the shallow northward flowing Antilles Current as well as the southward flowing Deep Western Boundary Current.

During fiscal year 2011, two cruises involving full-water-column CTD, lowered ADCP, and shipboard ADCP were conducted within the Florida Straits and east of Abaco Island, Bahamas. At each station, a package consisting of a Seabird Electronics Model 9/11+ CTD O_2 system, an RDI 150 kHz Workhorse Lowered Acoustic Doppler Current Profiler, a RDI 300 kHz Workhorse Lowered Acoustic Doppler Current Profiler, and 23 10-liter Niskin bottles, was to be lowered to the bottom. This provides profiles of velocity, pressure, salinity (conductivity),

temperature, and dissolved oxygen concentration. Water samples were collected at various depths and analyzed for salinity and oxygen concentration to aid with CTD calibration. Due to ship time issues in FY09 and FY10, the second cruise of FY09 slipped into early FY10, and the second cruise of FY10 slipped into early FY11. We report here on the two cruises actually completed during FY11.

The first cruise this year took place during Nov. 28 - Dec. 2, 2010 on the NOAA Ship Ronald H. Brown. The Brown cruise was substantially reduced due to ship time funding and the cancellation of the Sep 2010 cruise due to the Deep Water horizon oil spill. During this cruise, two CTD casts were conducted, three inverted echo sounders were telemetered and one PIES was recovered and redeployed. In addition two United Kingdom moorings were serviced. The second cruise was completed during Apr 13 – May 4, 2011 on the R/V Knorr. The stations on the Knorr cruises were occupied at the locations shown in Figure 2. During the spring cruise we deployed a University of Rhode Island (URI) designed PIES at site D. Several issues were encountered: the transducer model was not set in the firmware, resulting in too little power being sent to the transducer head resulting in inaudible pings. This was fixed by entering "secure" menu and inserting the transducer type. We also deployed an AOML designed SEADAT pies at site C and deployed a URI PIES at site B. Table 3 lists the cruise dates, bottle samples and the operations completed at the inverted echo sounder mooring sites.

FY	Date	Ship	Stations	Bottle Samples	Comments
2011	Apr 13 - May 4, 2011	Knorr	52	804 O2, 804 S	Deployed SEADATA at site C and PIES at site D and B. Telemerty at A, A2 and E.
2011	Nov 27 - Dec 19, 2010	Brown	2	20 S	Recover and redeploy site A PIES. Recovery and redeployment of two UK moorings. Telemetry at sites B, A2.
2010	Mar 23 - Apr 4, 2010	Oceanus	61	821 O2, 855 S	Telemetry data from one PIES and one CPIES were collected. Two PIES failed to telemeter. One PIES was recovered. One PIES and one CPIES were deployed.
2010	Nov 21 - Dec 6, 2009	Discovery	35	562 O2, 623 S	Telemetry data from one PIES were collected. Two PIES failed to telemeter. One PIES and one CPIES were recovered. Two PIES and one CPIES were deployed. One IES was lost.
2009	Apr, 2009	Brown	60	1112 O2, 1156 S	Telemetry data from three PIES and one CPIES were collected. One PIES was lost

2008	Sep, 2008	Cape Hatteras	17	105 O2, 174 S	Telemetry data collected from one PIES and one CPIES, three PIES were deployed, three PIES and one IES were recovered, one PIES and one IES were lost
2008	Apr, 2008	Seward Johnson	45	400 O2, 634 S	Telemetry data collected from four PIES/CPIES, and one PIES was recovered
2007	Sep, 2007	Brown	48	737 O2, 706 S	Telemetry data collected from five PIES/CPIES
2007	Mar, 2007	Brown	74	1092 O2, 1135 S	Telemetry data collected from five PIES/CPIES
2006	Sep, 2006	Seward Johnson	42	465 O2, 568 S	2 IES recovered, 1 IES lost (but data retrieved via telemetry), 7 IES deployed, and data retrieved via telemetry from 2 IES
2006	Mar, 2006	Brown	72	921 O2, 943 S, 391 nuts, 506 DOC/TOC, 80 DIC, 40 TALK	2 IES recovered, 2 IES deployed, data from 3 IES recovered via acoustic telemetry
2005	Sep, 2005	Brown	53	728 O2, 728 S	1 IES deployed, 2 IESs recovered, data from 3 IESs recovered via acoustic telemetry
2005	May, 2005	Knorr	70	1084 O2, 1180 S	1 IES deployed, data recovered from 3 IESs via acoustic telemetry
2004	Sep, 2004	Brown	42	634 O2, 629 S	5 IES mooring deployments
2003	Feb, 2003	Brown	54	844 O2, 843 S	3 IES Mooring recoveries, Short Seabeam in Florida Straits
2002	Jun-02	Brown	57	924 O2, 924 S	Extended Seabeam survey east of Abaco Island, SF6 samples.
2001	Apr-01	Oceanus	33	607 O2, 659 S	4 IES mooring deployments

Table 3: *Cruise dates and water samples taken for Large Vessel full water column surveys of the Deep Western Boundary Current. September 2006 and April 2008 cruises aboard the R/V Seward Johnson and the May 2005 cruise aboard the R/V Knorr were with ship time funded by NSF, while the November 2009 cruise was utilizing funding from the UK/NERC. Additional nutrient and carbon measurements that were taken during the March 2006 cruise were collected using base funds.*

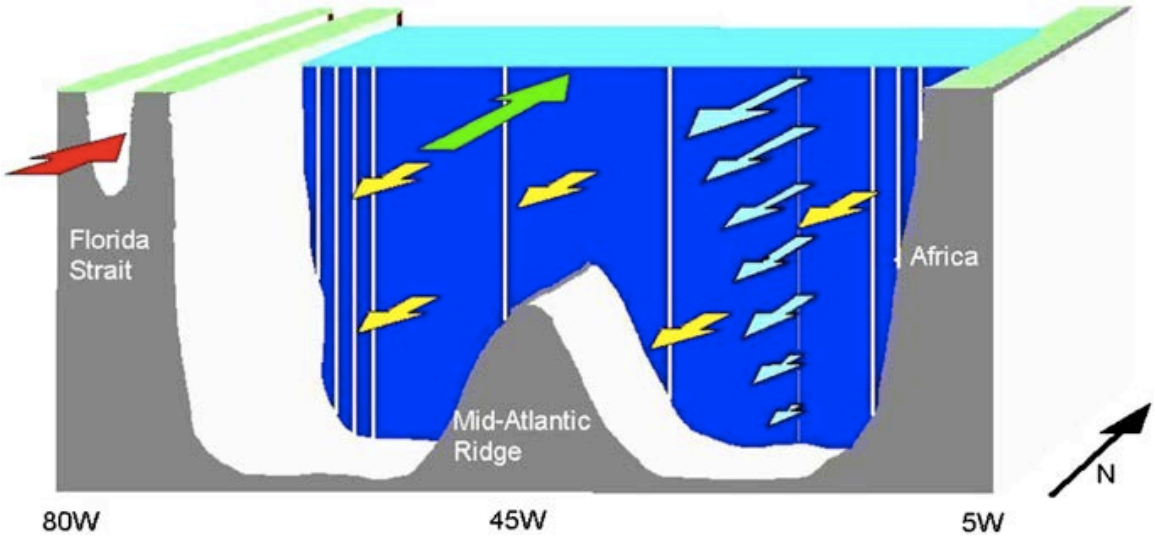


Figure 4*: Schematic of the MOC monitoring array at 26°N. The MOC is decomposed into three components: (1) Gulf Stream transport through the Florida Straits (red arrow), (2) the near-surface wind driven Ekman transport (green arrow) arising from the zonal wind stress, and (3) geostrophic (thermal wind) contribution (light blue arrows) calculated between adjacent pairs of ''moorings'' (vertical lines). Yellow arrows indicate a spatially constant velocity correction that ensures mass balance across the section. Modified from Rayner et al., 2011.*

Scientific Accomplishments:

Data from the Western Boundary Time Series project has been combined with data from the NSF-funded MOCHA program and the United Kingdom-NERC funded RAPID program to produce a published paper (Rayner *et al* 2011) detailing the time variability of the basin-wide, full-water-column, MOC of this international collaborative program (Figure 4). The technical changes and challenges found during the initial four years of the trans-basin RAPID-MOC/MOCHA/WBTS array are described in detail in this paper. The paper also discusses the observed changes over the first four years of the array, illustrating the ± ~25% time variability observed over the first four years at time scales of weeks to months.

The first four years of data from the RAPID-MOC/MOCHA/WBTS array at 26.5°N are used to study the seasonal variability of the Atlantic Meridional Overturning Circulation (AMOC) during 2004-2008 (Kanzow et al 2010). Among the key results of this study is that the MOC exhibits a significant annual cycle and that the geostrophic component of this annual cycle is dominated by variability near the eastern boundary of the basin. The 'best' seasonal cycle derived from the data suggests a peak-to-peak amplitude of just under 7 Sv, with a minimum in boreal spring and a maximum in boreal autumn. The study demonstrates that the fluctuations of the basin-interior geostrophic flows dominate those of the wind-driven Ekman flows. The study also demonstrates that aliasing of seasonal anomalies of the AMOC may explain the previously suggested downward trend in the AMOC determined from snapshot hydrographic sections.

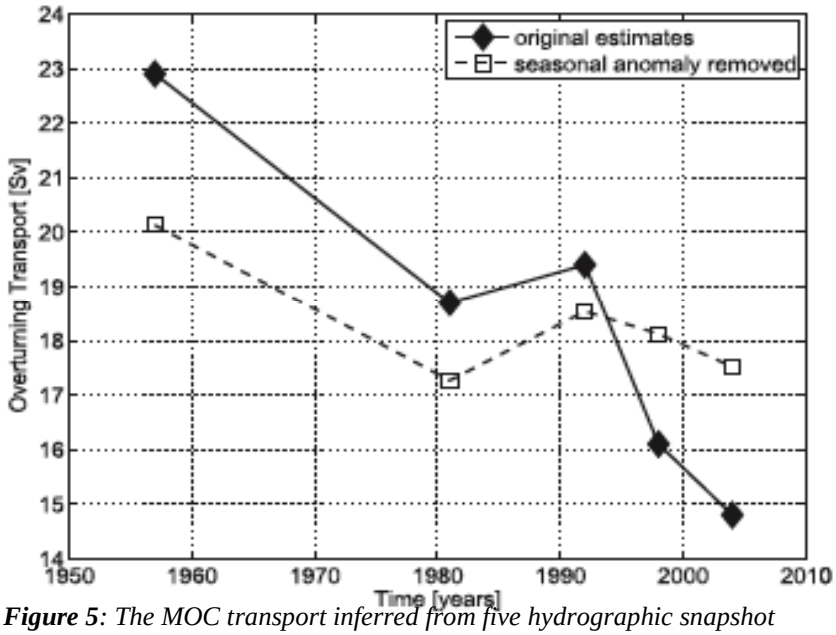
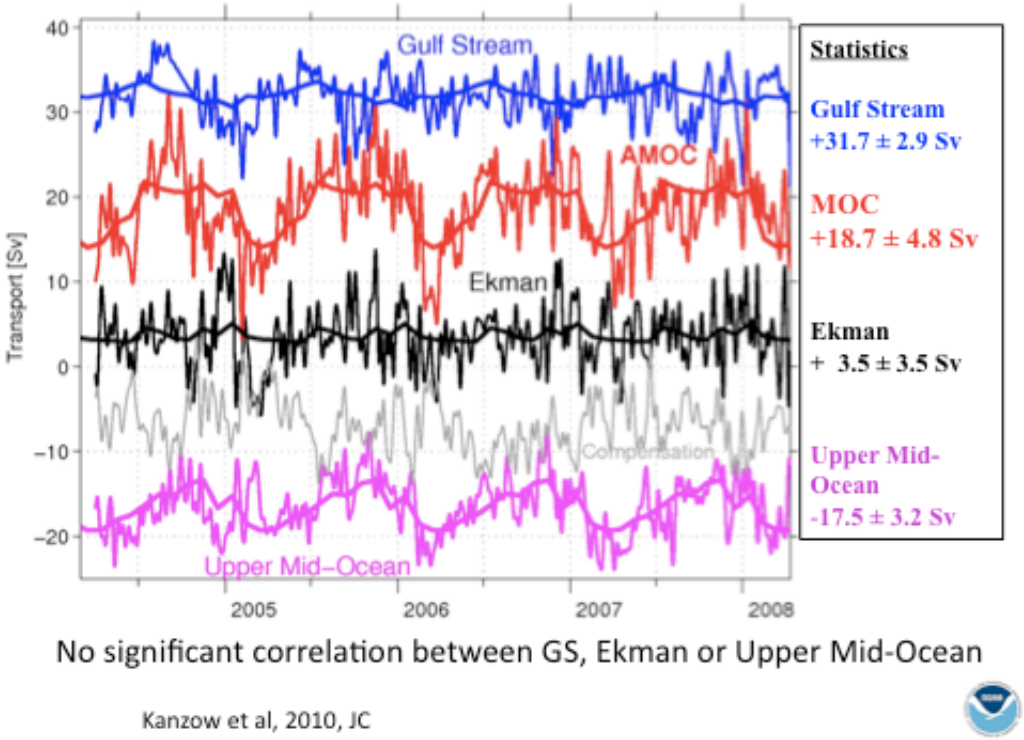


Figure 5*: The MOC transport inferred from five hydrographic snapshot estimates between 1957 and 2004 (solid diamonds), as reproduced from Bryden et al. (2005). The hydrography cruises were carried out in different seasons, namely, in October 1957, August–September 1982, July–August 1991, February 1998, and April 2004. The open squares represent the historical estimates of MOC transport after removal of the seasonal anomalies of MOC transport estimated in the study. Modified from Kanzow et al., 2010.*



Johns et al (2011) provide the first continuous time series of meridional heat transport in the global oceans, at a key latitude within the Atlantic basin where the heat transport is close to its maximum (Figure 6). The results should provide a valuable benchmark for testing ocean circulation models, coupled climate models, and indirect methods used for estimating ocean heat transport via residual or surface flux methods. The average, annual mean meridional heat transport across 26.58N for 2004–07 is 1.33 +/- 0.14 PW. The short-term variability of the heat transport is large, with a range from 0.2 to 2.5 PW and standard deviation of 0.4 PW. About half of this variability can be directly attributed to Ekman transport changes; the remainder is due to geostrophic circulation changes. The range of variability is consistent with eddy-permitting or eddy-resolving OGCMs; however, the geostrophic variability appears to play a larger role than previously suggested by models at this latitude. A seasonal cycle is evident, with maximum heat transport in boreal summer/fall and minimum in boreal spring, of amplitude 0.3 PW. While both Ekman transport and western boundary (Florida Current) variations contribute to this seasonal cycle, the main contribution is through interior ocean baroclinic changes forced by annual wind stress curl variability in the eastern basin. The meridional heat transport is highly correlated with changes in the strength of the meridional overturning circulation. The overturning circulation accounts for nearly 90% of the total heat transport, and the remaining heat transport, associated with velocity and temperature anomalies relative to their zonal means, is contained in a quasi-stationary gyre pattern, with little net contribution by mesoscale eddies.

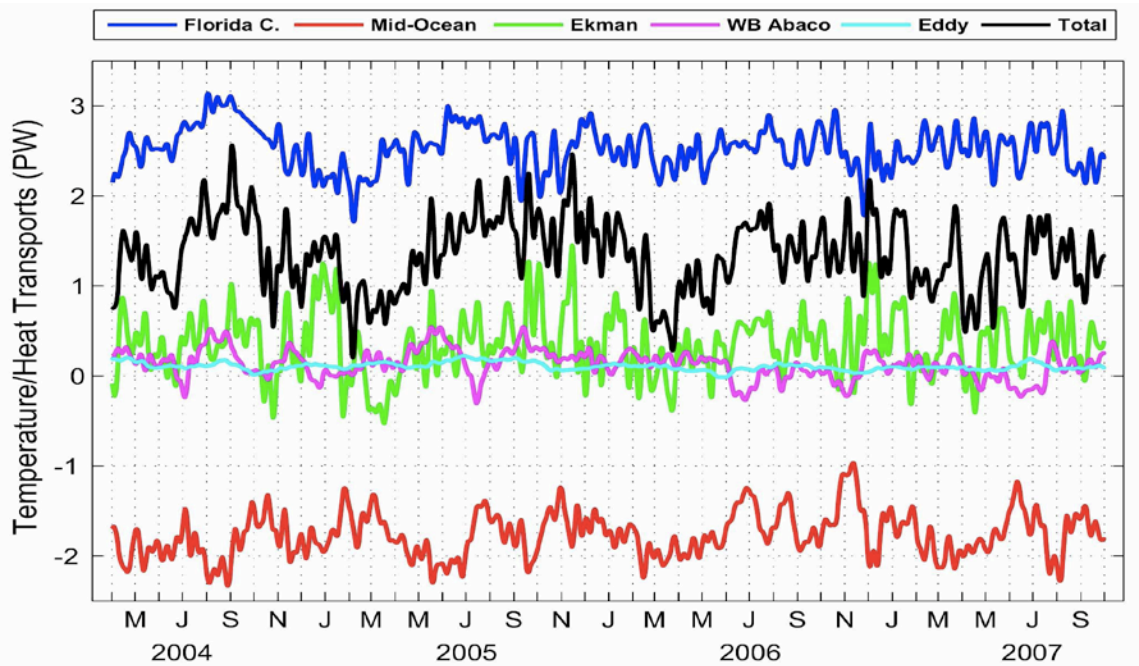


Figure 6 *Temperature transports (relative to 0ºC), for each of the section contributions to the net meridional heat transport at 26.5ºN (shown in black line). All components have been low-pass filtered to remove variance at periods shorter than 10 days. The total heat transport (black) and mid-ocean "eddy" heat transport (light blue) are the only ones that represent true heat fluxes, independent of temperature reference.*

More than two decades of hydrography on the Abaco line east of the Bahamas at 26°N reveals decadal variability in the salinity of classical Labrador Sea Water (cLSW), despite the long distance from its source region in the North Atlantic Ocean (van Sebille et al 2011). Hydrographic time series from the Labrador Sea and from the Abaco line show a pronounced step-like decrease in salinity between 1985 and 1995 in the Labrador Sea and between 1995 and 2010 at the Abaco line, suggesting a time lag between the two locations of approximately 9 years (Figure 7). The amplitude of the anomaly at the Abaco line is 50% of the amplitude in the Labrador Sea. A similar time lag and reduction of amplitude is found in the high-resolution OFES model, in which salinity anomalies can be observed propagating through the Deep Western Boundary Current as well as through a broad interior pathway. On its way south to the Abaco line, the cLSW becomes 8 standard deviations saltier due to isopycnal mixing with Mediterranean Outflow Water (MOW). Climatological data in the North Atlantic suggests that the mixing ratio of MOW to cLSW at the Abaco line is 1:4 and that no variability in MOW is required to explain the observed variability at the Abaco line. The data studied here suggest that decadal cLSW anomalies stay relatively coherent while getting advected, despite the important role of interior pathways.

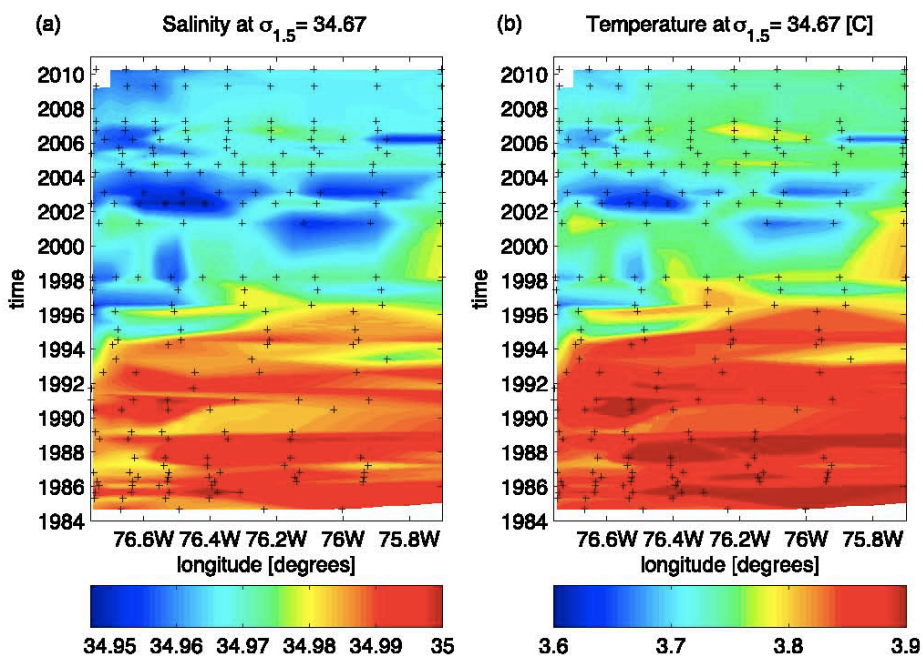


***Figure 7**: Hovmoller plots of (a) salinity and (b) temperature on the sigma1.5 = 34.67 kg/m3 density surface (the core of the classical Labrador Sea Water) just off the Abaco coast. The black plusses indicate locations and timing of conductivity-temperature-depth (CTD) stations. Additional CTD stations outside of the domain shown here were used for the interpolation toward the domain boundaries. This figure is an extension of a similar figure (on approximately the same color scale) by Molinari et al. [1998] which showed that between 1994 and 1996 the core of the cLSW freshened and became colder. This extension shows that since then temperature and salinity have not come back to 1980s levels.*

Baringer et al (2011) summarized the state of the meridional overturning circulation including an update of the meridional overturning circulation form the Rapid/MOC/MOCHA/WBTS array from 2004-09. In this paper they show that the 2010, the mean transport through the Florida Straits continued the decrease over the past four years to 30.7 +/- 1.5 Sv (95% confidence limits), lower than the 2009 31.3 +/- 1.2 Sv, 2008 31.7 +/- 2.2 Sv , and 2007 32.1+/- 1.0 Sv mean transports (error bars represent standard error of daily values using degrees of freedom calculated for each year, representing a typical decorrelation time scale of around 20 days). The annual mean of 2010 falls within the lowest quartile of mean annual values (32 +/- 0.14 Sv). Note that while recently the annual means appear to have decreased (trend of -0.88 +/- 0.85 Sv per decade from April 2004 to April 2009, 95% significance), there is only a very small significant long-term trend to the Florida Current transport (Fig 8; trend for full time series is -0.14 +/- 0.06 Sv per decade). The daily fluctuations of the Florida Current transport throughout the year are fairly similar to 2009 and generally fall within 90% confidence levels (Fig. 8).

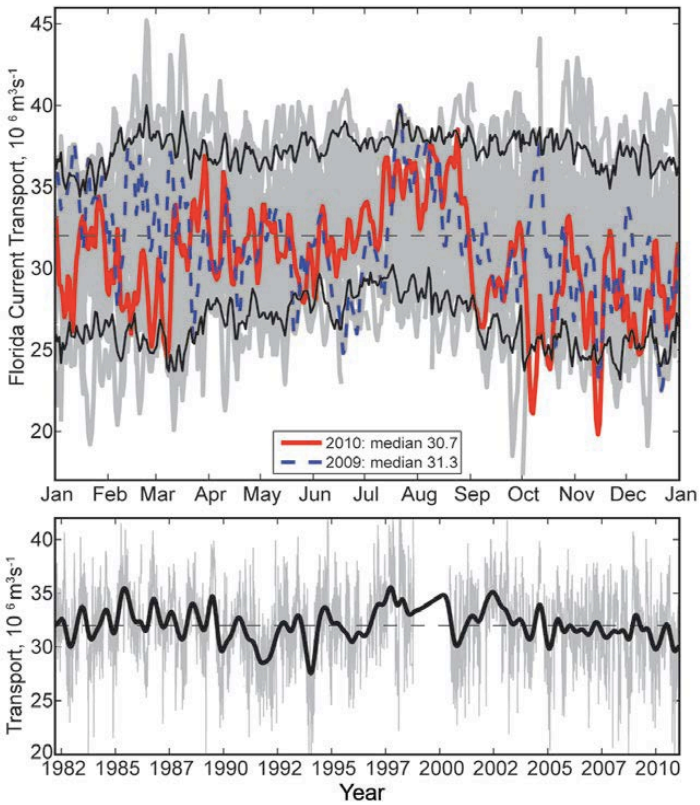


Figure 8 (top) *Daily estimates of the transport of the Florida Current during 2010 (red solid line) compared to 2009 (dashed blue line). The daily values of the Florida Current transport for other years since 1982 are shown in light gray and the 90% confidence interval of daily transport values computed from all years is shown in black (solid line); the long-term annual mean is dashed black. The mean transport in 2010 of 30.7 ± 1.5 Sv decreased for the fourth year in a row, below the long-term mean for the daily values of the Florida Current transport (32.2 Sv).* ***(bottom)*** *Daily estimates of the Florida Current transport for the full time series record (light gray), a smoothed version of transport (heavy black line; using a 30-day running mean six times) and the mean transport for the full record (dashed black). (Baringer et al 2011)*

In ongoing work, five years of data from dynamic height moorings, bottom pressure gauges, and pressure-equipped inverted echo sounders are used to study the time variability of the Deep Western Boundary Current (DWBC) at 26.5° in the Atlantic (Meinen et al 2012). Variations are found to well exceed those of the basin-wide Meridional Overturning Circulation (MOC), even when the deep transports are integrated as far as the western flank of the Mid-Atlantic Ridge (thereby integrating out all deep recirculation). The seasonal variability of the DWBC flow is found to be of marginal statistical significance with only five years of data, and that variability is more tightly confined to the boundary than had previously been believed. The strong variability at fairly short (days to months) time scales illustrates the necessity of time-series observations in order to study the MOC variability in the Atlantic.

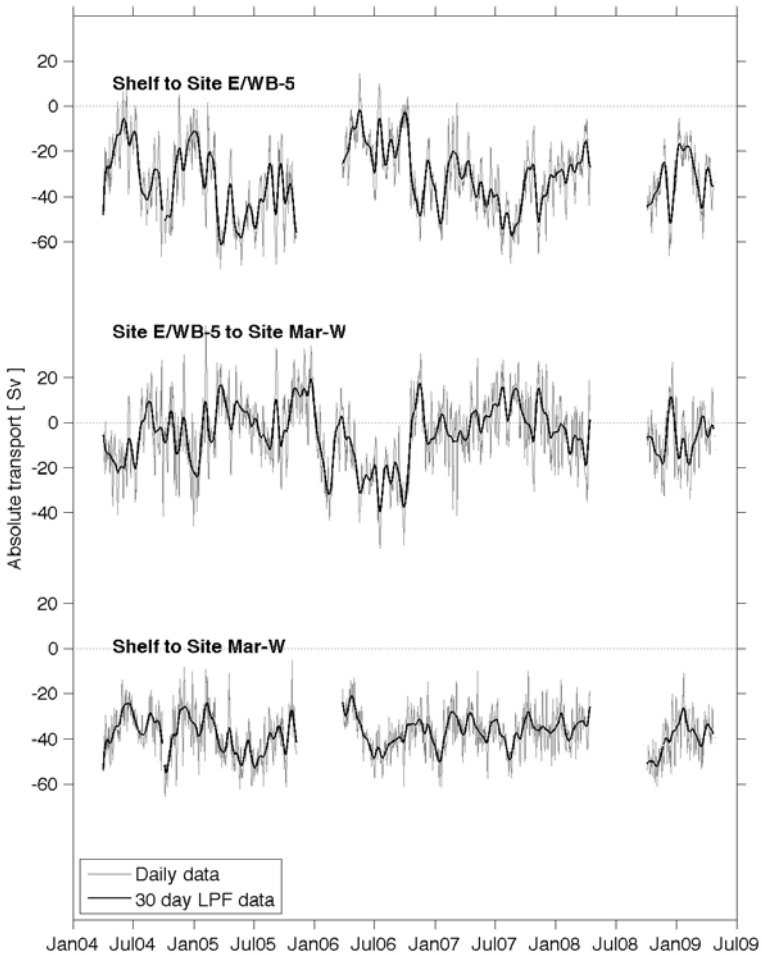


***Figure 9**: Absolute geostrophic transport estimated between 800 and 4800 dbar (or the bottom) and in the indicated spans between moorings along the 26°N RAPID-MOC/MOCHA/WBTS array. Both daily data (gray) and 30-day low-pass filtered data (black) are shown; gaps indicate instrument failures. Note that due to the lack of time-mean velocity information in the Site E/WB-5 to Mar-W span for leveling the bottom pressure data, the lower two lines may have an unknown mean offset. Modified from Meinen et al., (2012).*

Project web sites:

http://www.aoml.noaa.gov/phod/floridacurrent/
http://www.aoml.noaa.gov/phod/wbts/
http://www.noc.soton.ac.uk/rapidmoc/
http://www.rsmas.miami.edu/users/mocha/

2.1 Education and Outreach

The WBTS project has been involved informally with numerous graduate students and post-doctoral fellows from the University of Miami and other universities. For example one graduate student, Benjamin Shaw recently completed his M.S. thesis at the University of Miami using data from the WBTS project along with data from satellites and numerical model output. Dr. Erik van Sebille, a postdoctoral fellow at the University of Miami, is spent 2011 working on research utilizing data from the WBTS program. Graduate students and post-doctoral fellows are encouraged to use this data for theses and papers, although no explicit analysis is funded under this proposal. We have hosted three "Teachers-at-Sea" on board our cruises since 2006 and would welcome more participation. Author Dallas Murphy volunteered for our cruises and published a book entitled "To Follow The Sea" which sought to explain the importance of the Meridional Overturning Circulation to lay-science readers. We have participated in the "Adopt a Drifter" program where three schools from around the country adopted two drifters deployed on our cruises. Dr. M. Baringer has given numerous science outreach presentations to area schools.

3. Publications and Reports

3.1 Publications by Principal Investigators

Referred Publications Directly Related to the WBTS Project (electronic versions of published articles are available via hyperlink):

FY2012

Meinen, C. S., William E. Johns, Silvia L. Garzoli, Erik van Sebille, Darren Rayner, Torsten Kanzow, and Molly O. Baringer, 2011. Variability of the Deep Western Boundary Current at 26.5°N during 2004-2009. *Deep-Sea Res., accepted.*

van Sebille, Erik, Molly O. Baringer, William E. Johns, Christopher S. Meinen, Lisa M. Beal, M. Femke de Jong, and Hendrik M. van Aken, 2011. Propagation pathways of classical Labrador Sea Water from its source region to 26o N, Journal of Geophysical Research Oceans, 116, C12027, doi:10.1029/2011JC007171.

FY2011

Baringer, M. O., T. O. Kanzow, C. S. Meinen, S. A. Cunningham, D. Rayner, W. E. Johns, H. L. Bryden, Eleanor Faika-Williams, J. J-M. Hirschi, M. P. Chidichimo,L. M. Beal and J. Marotzke, 2011. Meridional Overturning Circulation Observations in the Subtropical North Atlantic, in State of the Climate in 2010, Blunden, J., D. S. Arndt,

M. O. Baringer (eds.), *Bull. Am. Met. Soc*., 92, S95–S98. doi: 10.1175/1520-0477-92.6.S1

Johns, W. E., M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, H. L. Bryden, J. Hirschi, J. Marotzke, C. Meinen, B. Shaw, and R. Curry, 2010. Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5 ºN. *J. Clim*., 24(10):2429-2449.

Kanzow. T., S.A. Cunningham, W.E. Johns, J. J-M. Hirschi, J. Marotzke, M. O. Baringer, C.S. Meinen, M. P. Chidichimo, C. Atkinson, L. M. Beal, H. L. Bryden, J. Collins, 2010. Seasonal variability of the Atlantic meridional overturning circulation at 26.5ºN. *Journal of Climate*, *23*, doi: 10.1175/2010JCLI3389.1171.

Longworth, H. R., H. L. Bryden, M. O. Baringer, 2011. Historical Variability in Atlantic meridional baroclinic transport at 26.5ºN from boundary dynamic height observations. *Deep-Sea Research Part II*, Topical Studies in Oceanography, Volume 58:1754-1767, ISSN 0967-0645, DOI: 10.1016/j.dsr2.2010.10.057.

Rayner, D., Joel J.-M. Hirschi, Torsten Kanzow, William E. Johns, Stuart A. Cuningham, Paul G. Wright, Eleanor Frajka-Williams, Harry L. Bryden, Christopher S. Meinen, Molly O. Baringer, Jochem Marotzke and Lisa M. Beal, 2010.Monitoring the Atlantic Meridional Overturning Circulation, *Deep-Sea Res.*, *Part II*, Topical Studies in Oceanography, Volume 58;1744-1753, ISSN 0967-0645, DOI: 10.1016/j.dsr2.2010.10.056.

Other FY2011 Publications by project PIs:

Blunden, J., D. S. Arndt, M. O. Baringer, 2011: State of the Climate in 2010. Bull. Amer. Meteor. Soc., 92, S1–S236. doi: 10.1175/1520-0477-92.6.S1

Dong, S., M. Baringer, G. Goni and S. Garzoli, 2011. Importance of the assimilation of Argo Float Measurements on the Meridional Overturning Circulation in the South Atlantic. Geophysical Research Letters, 38, L18603, doi:10.1029/2011GL048982.

Dong, S. S. Garzoli and M. Baringer, 2011. The Role of inter-ocean exchanges on decadal variations of the northward heat transport in the South Atlantic, J. Phys. Oceano., 41(8):1498-1511.

Garzoli, S.L and R. Matano, 2011: The South Atlantic and the Atlantic Meridional Overturning Circulation. Deep-Sea Research II, 58(17-18):1837-1847, doi:10.1016/j.dsr2.2010.10.063.

Lee S.-K., W. Park, E. van Sebille, M. O. Baringer, C. Wang, D. B. Enfield, S. Yeager, and B. P. Kirtman, 2011. What Caused the Significant Increase in Atlantic Ocean Heat Content Since the mid-20th Century? Geophysical Research Letters, doi:10.1029/2011GL048856.

Lumpkin, R. and S. L. Garzoli, 2011: Interannual to Decadal Variability in the Southwestern Atlantic's Surface Circulation. *Journal Geophysical Research - Oceans*, 116, C01014, doi:10.1029/2010JC006285.

Perez, R.C., S.L. Garzoli, C.S. Meinen, and R.P. Matano, 2011: Geostrophic Velocity Measurement Techniques for the Meridional Overturning Circulation and Meridional Heat Transport in the South Atlantic. *Journal of Atmospheric and Oceanic Techology*, 28:1504-1521.

Conference Presentations:

FY2012

Baringer, M., S. Dong, S. Garzoli, G. Goni, S. Lee, R. Lumpkin, C. Meinen, and R. Perez, Sustained Observations that contribute to understanding the Meridional Overturning Circulation, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Dong, S., M. Baringer, S. Garzoli, G. Goni, and C. Meinen, Observations for Climate: The contribution of the XBT network to climate studies, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Frajka-Williams, E., H. Bryden, S. Cunningham, J. Hirschi, W. Johns, T. Kanzow and C. Meinen, Atlantic Meridional Overturning Circulation, Compensation at the western boundary between the Gulf Stream and Interior Transport, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Frajka-Williams, E., M. Baringer, H. Bryden, S. Cunningham, J. Hirschi, W. Johns, C. Meinen, and D. Rayner, Atlantic Meridional Overturning Circulation: Towards a decade-long time series of observations at RAPID-MOCHA 26N, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Garzoli, S., G. Johnson, B. Sloyan, and R. Wanninkhof, Observations for climate: Expanding to the Deep Ocean, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Johns, W., M. Baringer, L. Beal, H. Bryden, S. Cunningham, R. Curry, J. Hirschi, T. Kanzow, J. Marotzke, and C. Meinen, Atlantic Meridional Overturning Circulation: New estimates of Atlantic Ocean Heat Transport at 26.5°N from the RAPID-MOCHA Array, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Lumpkin, R., S. Garzoli, G. Goni, and V. Hormann, Observations for Climate: NOAA's Global Drifter Program, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Lumpkin, R., M. Baringer, S. Garzoli, G. Goni, and C. Schmid, Observations for Climate: Evaluating the Global Ocean Observing System, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Meinen, C. S., S. L. Garzoli, R. C. Perez, and A. Piola, Atlantic Meridional Overturning Circulation: Deep Western Boundary Current transport variability in the South Atlantic - Preliminary results from a pilot array at 34.5◦S, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Meinen, C. S., W. E. Johns, S. L. Garzoli, E. van Sebille, D. Rayner, T. Kanzow and M. O. Baringer, Atlantic Meridional Overturning Circulation: Variability of the Deep Western Boundary Current at 26.5◦N during 2004-2009, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Roemmich, D., S. Garzoli, G. Johnson, W. Owens, and S. Riser, Observations for climate: Global ocean temperature, salinity and circulation measured by the Argo Program, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Szuts, Z., M. Baringer, and C. Meinen, Atlantic Meridional Overturning Circulation: Salinity and water mass transports in the Florida Straits, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

van Sebille, E., M. Baringer, L. Beal, F. de Jong, W. Johns, C. Meinen, and H. van Aken, Atlantic meridional overturning circulation: Propagation pathways of classical Labrador Sea Water from its source region to 26N, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

Wanninkhof, R., M. Baringer, J. Bullister, A. Dickson, R. Feely, G. Johnson, C. Langdon, F. Millero, C. Mordy, C. Sabine, and J.-Z. Zhang, Observations for Climate: The NOAA component of the CLIVAR CO2/Tracer Repeat Hydrography Program, 2011. (2011 World Climate Research Program Open Science Conference, October 24-28, Denver, Colorado.)

FY2011

Atkinson, C. M. Baringer, L. Beal, H. Bryden, M-P. Chidichimo, J. Collins, S. Cunningham, J. Hirschi, W. Johns, H. Johnson, T. Kanzow, J. Marotzke, D. Marshall, C. Meinen, A. Mujahid, D. Rayner, Z. Szuts, E. Frajka-Williams, Meridional overturning circulation and heat flux array at 26.5°N: Variability observed at periods of minutes to years during the period from April 2004 to April 2009, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

Atkinson. C, M. Baringer, L. Beal, H. Bryden, M-P. Chidichimo, J. Collins, S. Cunningham, J. Hirschi, W. Johns, H. Johnson, T. Kanzow, J. Marotzke, D. Marshall, C. Meinen, A. Mujahid, D. Rayner, Z. Szuts, E. Frajka-Williams, Meridional overturning circulation and heat flux array at 26.5°N: Variability observed at periods of minutes to years during the period from April 2004 to April 2009, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

Garzoli, S. L., and C. S. Meinen, Deep Western Boundary Current variability and signal attribution in the North Atlantic, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

Meinen, C. S., W. E. Johns, S. L. Garzoli, S. A. Cunningham and T. Kanzow, Variability of the Deep Western Boundary Current at 26.5°N, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

Meinen, C. S., Variability of the Meridional Overturning Circulation: Ocean Dynamics that Matter to Climate, 2011. (2011 Paul J. McInerney Memorial Lecture, March 17, Millersville University, Millersville, Pennsylvania.)

Szuts, Z., C. Meinen, E. McDonagh, and J. Marotzke, Calibrating the Florida Straits submarine cable for salinity transport, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

van Sebille, E., W. Johns, M. Baringer, C. Meinen, L. Beal, M. F. de Jong, H. van Aken, Propagation pathways of classical Labrador Sea Water from its source region to 26°N, 2011. (2011 RAPID-U.S. AMOC International Science Meeting, July 12-15, Bristol, United Kingdom.)

3.2 Other Relevant Publications (more than 50 publications have cited or used results from this work in fiscal year 2011)

Frajka-Williams, E., S. A. Cunningham, H. Bryden, and B. A. King, Variability of Antarctic Bottom Water at 24.5°N in the Atlantic, J. Geophys. Res., 116, C11026, doi:10.1029/2011JC007168, 2011.