Meridional Overturning Variability Experiment

Uwe Send
Scripps Institution of Oceanography, La Jolla CA

1. Table of Contents

2. Project Summary 1
3. Accomplishments 2
4. Education and Outreach 9
5. Publications and Reports 10

1. Abstract

MOVE has been monitoring the lower southward branch of the Atlantic Meridional Overturning Circulation (AMOC) at 16°N for 9 ½ years now and is producing the longest directly observed timeseries of mass transports in this system. The annual at-sea work for servicing three moorings and three PIES (bottom pressure sensors with inverted echosounding) has been carried out successfully, in conjunction with the annual NTAS cruise. All 40 instruments returned good data, and a preliminary transport timeseries have been constructed, showing a weakening trend of the AMOC of 0.35Sv/yr over the length of the timeseries. This is in agreement with a coupled climate model hindcast, suggesting multi-year climate predictability. Future work consists of making the array more efficient, reducing field work and enabling data telemetry.

2. Project Summary

The meridional overturning circulation (MOC) in the Atlantic Ocean is one of the major oceanic climate drivers of the globe since it is the mechanism for most of the large heat transport carried by the Atlantic Ocean, with demonstrated impacts and control on northern hemisphere and global climate. Variations in this circulation and the associated heat transport, both due to natural or anthropogenic effects, are of utmost importance but have been impossible to observe directly to date. MOVE is the first program which tackled this problem by attempting to install and sustain an observing system for the lower branch (deep, cold return flow) of the overturning circulation in the Atlantic.

In the year 2000 the German CLIVAR programme initiated the circulation monitoring array (MOVE) in the subtropical west Atlantic along 16N, in order to observe the transport fluctuations in the North Atlantic Deep Water layer. Since then, three (and later two) “geostrophic end-point moorings” and bottom pressure sensors, plus one traditional current meter mooring on the slope have been used to cover the section between the Lesser Antilles (Guadeloupe) and the Midatlantic Ridge. The goal is to determine the transport fluctuations

through this section, using dynamic height and bottom pressure differences between the mooring for estimates of the geostrophic transport. It has been shown that on long timescales this is a good approximation to the total southward (and by mass balance also northward) MOC transport.

The NOAA project MOVE, started in 2006, is the continuation of the MOVE transport array, while being complemented on the eastern side of the Atlantic with a German-funded and operated mooring (near the Cape Verde islands). To date, the array has delivered over 95% data return, and due to the built-in redundancy, transports are available now for the full 9.5 years since initiation of the program. Weakening trends in the circulation are starting to be visible, and with some more years of observations the reliability/significance of trend estimates will increase. The observed weakening transport is in agreement with a coupled climate model hindcast, and if confirmed would allow multi-year climate predictability. In addition to direct comparison with climate models (for validation or skill assessment), the MOVE data may also lend themselves for directly constraining climate models.

The MOVE array also contributes to closing a recognized present gap in the sustained ocean climate observing system - techniques and programs for monitoring the circulation and mass/heat/freshwater transports of major current systems. This was clearly identified as a major need at the OceanObs09 conference in Venice. Depending on the intensity, width, and depth extension of the current to be observed, different approaches and technologies exist now which allow implementation and maintenance of such “transport reference sites”. For broad-scale and deep-reaching circulations, the MOVE approach of fixed-point installations with moored and bottom-mounted instruments to obtain horizontally and vertically integrated measurements throughout the watercolumn is promising. MOVE is one of the first sustained US sites which are aimed at filling this gap in the global ocean observing system. The present proposal covers the next 5 years of operation of the MOVE system.

3. Accomplishments

In the reporting period, the MOVE mooring array was serviced on a research cruise with the RV “Ron Brown” in June 2009, from Charleston to Barbados. Figure 1 shows the cruise track in the work area. Moorings MOVE4, MOVE3, and MOVE1 were recovered successfully and data from the PIES at locations MOVE3, MOVE2, and MOVE1 were retrieved acoustically. At MOVE3 there were two PIES and the older one was recovered now, leaving one behind. In 2010 all PIES will be doubled up, in order to have 4-year deployments with 2-year overlap at each site. The PIES at MOVE7 was recovered with good data and was returned to the owners in Germany. The data from the moored instruments are complete and of good quality. Raw data processing has been performed, and scientific data analysis is now possible with the data, some preliminary results are shown below.

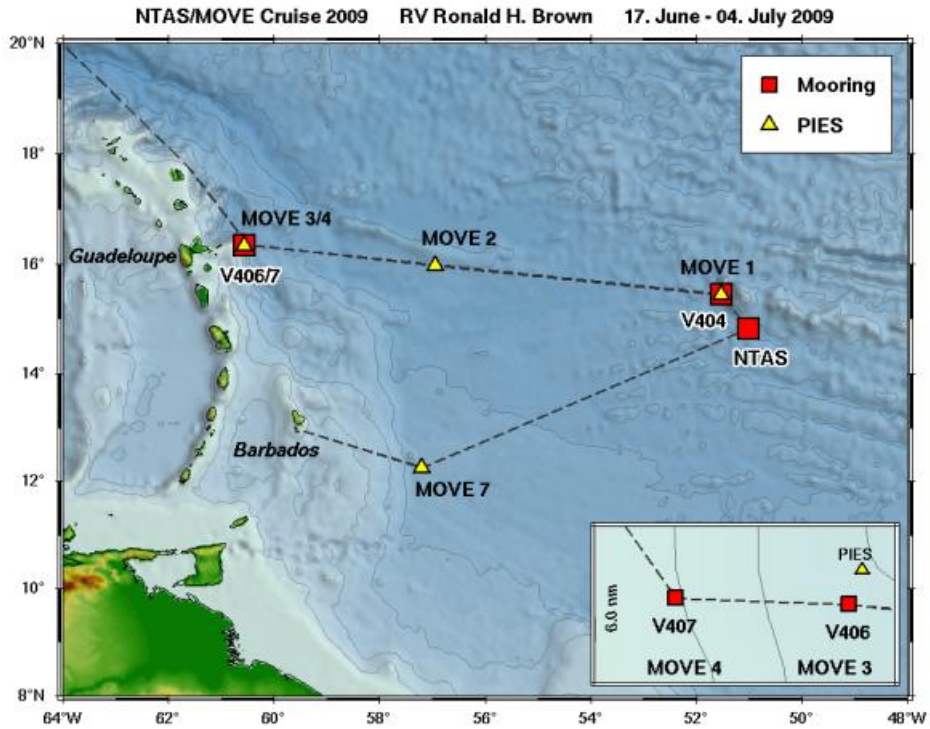

Figure 1: *Map of cruise track, moorings MOVE1, MOVE3, MOVE4, and pressure sensors/inverted echosounders (PIES) at locations MOVE1, MOVE2, MOVE3, MOVE7. Shown also is the location of the NTAS mooring which was serviced during the cruise by WHOI.*

Much of the raw data processing and calibration was carried out during the cruise. Of particular interest was the comparison of the new acoustic Nortek Aquadopp current meters with the old mechanical RCM ones which still belonged to partner groups in Europe. For this one overlapping year we had deployed them both at co-located depths, to test whether we might introduce biases by permanently moving from one type to the other. The following figures and tables show the encouraging comparisons at two such locations:

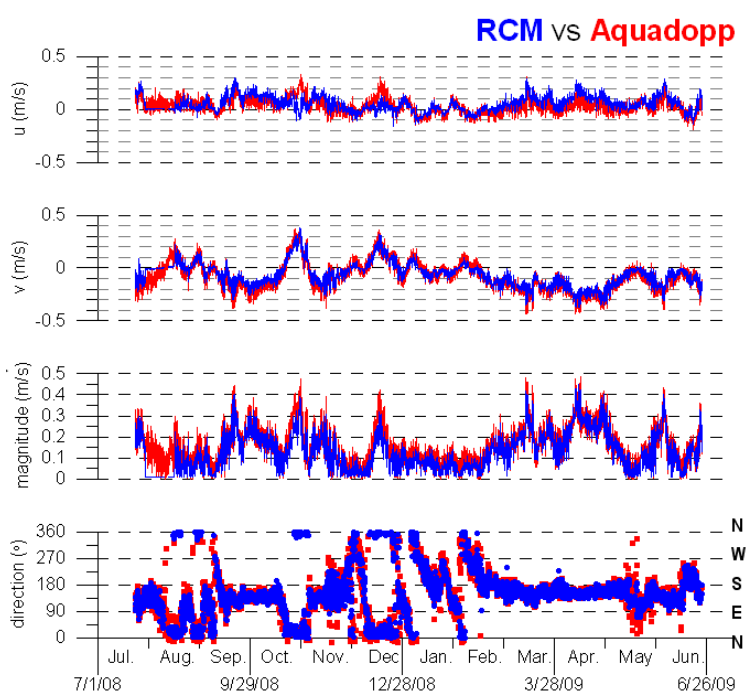

Figure 2: *Comparison of the mechanical rotor RCM and acoustic Aquadopp current meters at 867m depth on mooring M3. The longer scale variability and amplitudes/directions track each other very well.*

		u (m/s)	v (m/s)	Magnitude (m/s)	Direction (°)
Mean	RCM	0.05	-0.07	0.13	148
	Aqua.	0.04	-0.08	0.15	142
Std. Dev.	RCM	0.07	0.11	0.09	73
	Aqua.	0.07	0.13	0.09	72
Max.	RCM	0.30	0.38	0.45	359
	Aqua.	0.33	0.37	0.48	359
Min.	RCM	-0.16	-0.38	0.01	0
	Aqua.	-0.19	-0.44	0.00	0
Vector mean	RCM	-		0.09	144
	Aqua.			0.09	153
RMS Difference		0.06	0.04	0.04	28

Table 1: *Comparison of the mechanical rotor RCM and acoustic Aquadopp current meters at 867m depth on mooring M3. The mean amplitudes and directions are in good agreement, the main differences come from high-frequency variability.*

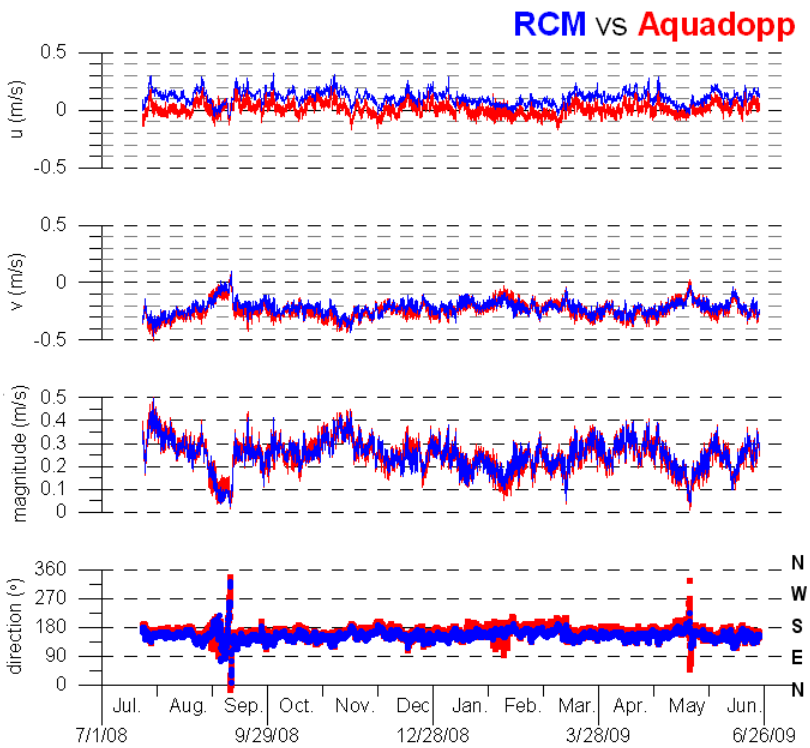

Figure 3: *Comparison of the mechanical rotor RCM and acoustic Aquadopp current meters at 2300m depth on mooring M3. The mean amplitudes are larger and in good agreement, even though the variability is less (smoother curves) than at 867m.*

		u (m/s)	v (m/s)	Magnitude (m/s)	Direction (°)
Mean	RCM	0.11	-0.22	0.25	154
	Aqua.	0.01	-0.24	0.25	162
Std. Dev.	RCM	0.06	0.06	0.07	15
	Aqua.	0.05	0.07	0.07	16
Max.	RCM	0.32	0.10	0.49	323
	Aqua.	0.26	0.09	0.52	352
Min.	RCM	-0.06	-0.46	0.03	6
	Aqua.	-0.17	-0.50	0.01	0
Vector mean	RCM	-		0.25	153
	Aqua.			0.24	178
RMS Difference		0.03	0.03	0.02	8

Table 2: *Comparison of the mechanical rotor RCM and acoustic Aquadopp current meters at 2300m depth on mooring M3. The large means and amplitudes agree well, but a small difference in direction is noted.*

As always, extreme care is required for the calibration of the 36 microcat temperature/conductivity sensors, since the accuracy of the density, dynamic height, and geostrophic transport estimates is very sensitive to any offsets in those sensors. Like in previous years, all microcats that were recovered (and also those which were going to be deployed) were attached to the CTD rosette and simultaneous vertical profiles were recorded with the CTD system and the attached microcats. In addition, the CTD conductivity probe was calibrated with water samples and high-precision salinometry carried out on board during the cruise. This worked extremely well, consistent results were achieved to very high precision, also in excellent agreement with microcat calibrations from previous years. Careful processing of the entire data ensembles then allows calibration of T, C, and S to the required accuracy for transport estimates.

Each mooring was re-deployed within less than 24 hours of recovery, due to the short time at sea available. This was only possible by having enough equipment at hand to deploy at least one complete mooring without “turning around” any recovered instruments. Later during the cruise, instruments from the first recovered moorings could be re-used for new deployments. The deployments carried out in 2009 were the first without borrowed instruments, all microcats, current meters, and acoustic releases are now from NOAA MOVE purchases.

Apart from the now omitted RCM current meters (replaced by the Aquadopps), the moorings were re-deployed in a nearly equivalent configuration as in the previous period. The configuration is still sparser than desirable, so that more instruments will need to be purchased from future funds. The tables below give information about the PIES and moorings deployed and the material contained in them. Note that PIES remain deployed for nominally 4 years.

PIES Deployments during RB-07-02, 04/2007, and OC 449/1, 07/2008, and RB-09-03, 06/2009

Site	*PIES s/n*	*Position*	*Water Depth*	*Depl. date/ period*
MOVE 3	197 SIO	16N21.36 60W29.33	4955m	15-Apr-2007 - 23-Jun-2009
MOVE 3	200 SIO	16N20.29 60N29.31	4900m	22-Jul-2008
MOVE 2	127 IFM	15N59.28 56W56.29	4943m	23-Apr-2007
MOVE 1	180 SIO	15N27.04 51W31.62	4965m	24-Apr-2007
MOVE 7	128 IFM	12N15.47 57W12.07	4454m	17-Apr-2007 – 03-Jul-2009

Mooring Deployments during cruise RB-09-03, June 2009

Site	*Mooring ID*	*Position*	*Water Depth*	*Depl. Date*
MOVE 4	MOVE4-09	16N20.00 60W36.45	3000m	24-Jun-2009
MOVE 3	MOVE3-09	16N20.30 60W30.30	4960m	25-Jun-2009
MOVE 1	MOVE1-09	15N27.00 51W30.50	4970m	28-Jun-2009

Mooring Instrumentation and Equipment:

Site	*Nortek Aquadopp*	*Seabird 37 MicroCat IM*	*Acoustic Release*	*17" glass Float*
MOVE 4	2	-	2	31
MOVE 3	2	21	2	62
MOVE 1	-	15	2	38

Each Mooring is equipped with 2 Elkins oceanographic titanium swivel and Esmet stainless oceanographic swivel, in total are 6 titanium and 6 stainless swivel deployed.
Each Mooring has a Top-Floatation element (Aluminum Frame with 2 17" glass floats), equipped with an Iridium-Beacon, a VHF-Radio-Transmitter and a Xenon-Flasher.

The cross-sectional layout of the MOVE section as deployed now is shown in figure 4.

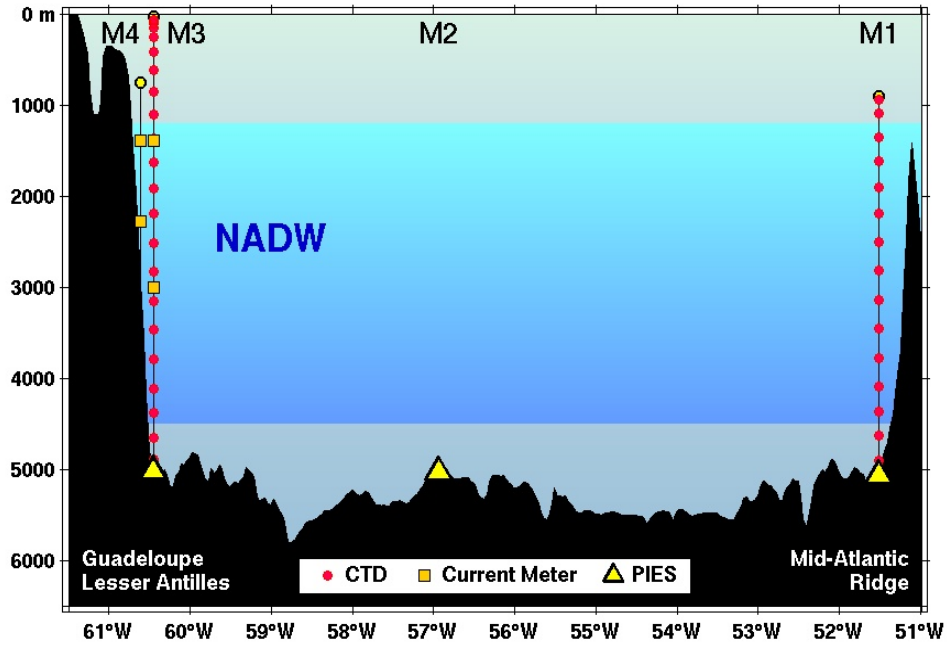

Figure 4: *Placement of moorings and sensors along the MOVE section as now deployed.*

After the cruise, work concentrated on analyzing the data in order to obtain useful and reliable estimates of the various transport components in the deep southward return flow of the meridional overturning circulation (MOC), i.e. the transport in the NADW (North Atlantic Deep Water). Since we now had an unprecedented 9½ -year timeseries at hand, a special effort was made to prepare a complete record of data for the July MOCA conference in Montreal where the results were presented. Some of those are shown below.

All three NADW transport components that are estimated by the MOVE array are plotted in figure 5. The "internal" part is the sheared (thermal wind) geostrophic transport relative to 4950db calculated from the microcats. The "external" one is the transport estimated from bottom pressure gradients at 4950m via the PIES data (mean&trend for each year is removed, thus only intra-annual variability is available). The "boundary" transport is derived from the current meters on the continental slope.

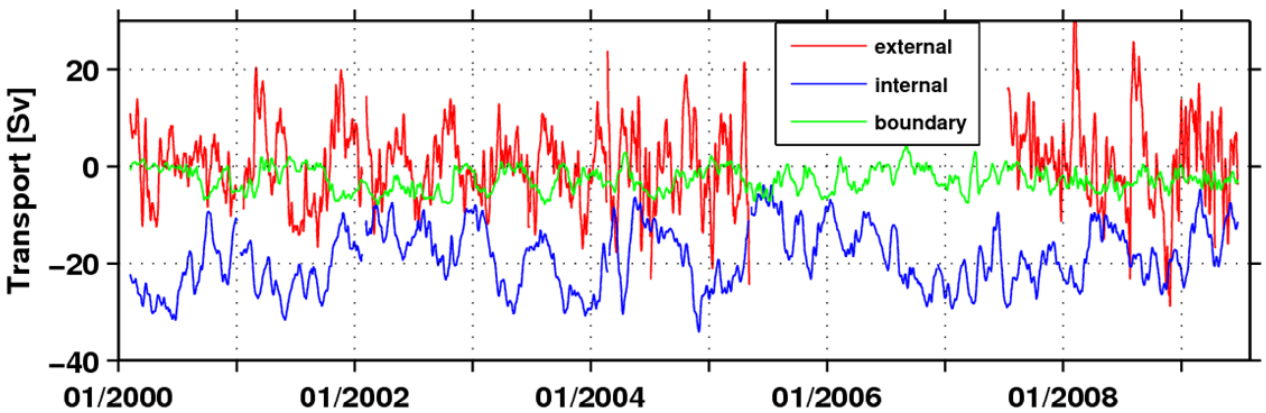

Figure 5: *Complete 9½ year timeseries of the three NADW transport components.*

Very large intra-seasonal variability in both external and internal transports is visible in Figure 5 (typically 20Sv each) – these result from Rossy waves, and they represent noise for the MOC estimates intended.

For long-term mean and trend we now make the following assumptions:

- the external component does not contribute to a trend, but adds noise → do not include it
- in model simulations the MOC variability is in the internal/sheared flow, so this also supports the approach to omit the external transport
- assume that on LONG TIME SCALES watermass boundaries must be zero-flow levels, i.e. 1180db (AAIW-NADW) or 4700db (NADW-AABW).

With that, the Internal+Boundary transport, shifted to make the MEAN at 1180db zero, gives the timeseries shown in figure 6 (note that total short-term variability may be different, since external/bottom fluctuations missing).

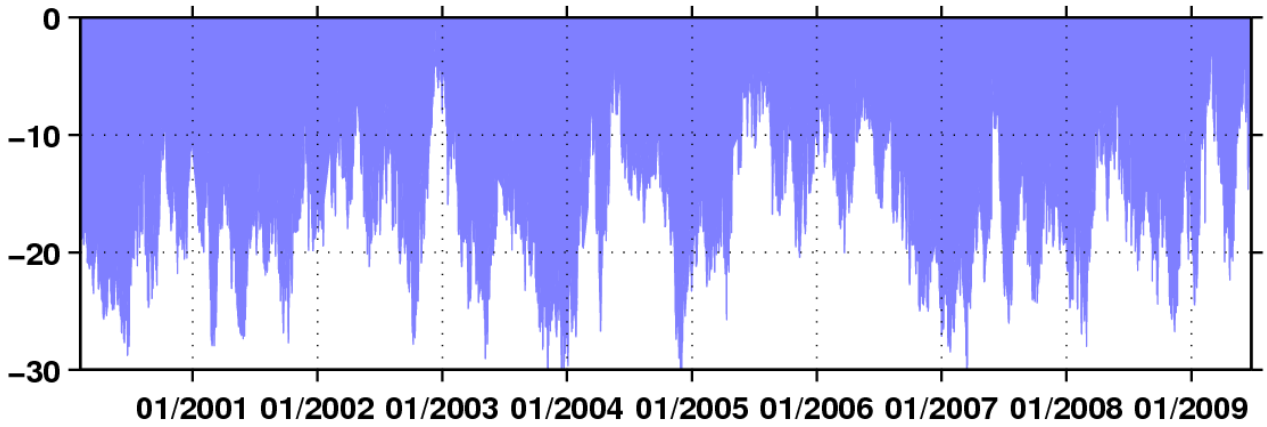

Figure 6: *Internal+boundary transport, shifted to make the MEAN at 1180db zero, giving a mean of -16.3Sv.*

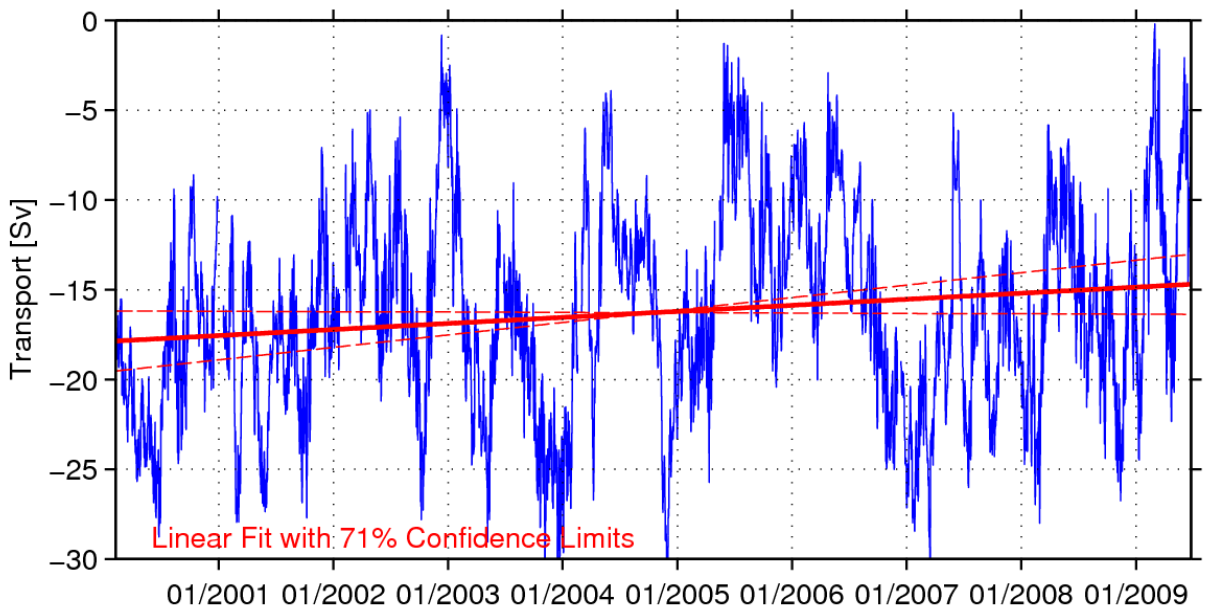

Figure 7: *Trend line through the transport of figure 6, with 71% confidence limits.*

The result from the trend line fit in figure 7 gives

- **trend = +0.35 Sv/a, i.e. the MOC has a decrease of about 3Sv over the measurement period**
- **with 85% certainty there is a trend larger than 0**
- **there are 45 degrees of freedom**

Whether this weakening trend is real will require a few more years of observations, but the observed rate is consistent with model simulations (like the FLAME model) which show natural variability with 8-year fluctuating trends of also 0.3Sv/year.

Further, coupled model hindcasts/forecasts initialized by relaxing to observed SST (Latif, Keenlyside, et al), show multidecadal variability with 8-year trends going up to +/-0.4Sv/yr. These allow 1-10year predictive skill: most recently, a weakening of the MOC of about 0.4Sv/yr is observed (and expected to continue), and should make the next decade cooler in Europe/N.America. Our data are consistent with those model simulations as well, and we are collaborating with that group to extend their runs to cover all of the MOVE period. We hope that this will lead to a publication in *Nature*.

The MOVE transport timeseries being the longest directly observed component of the AMOC system, this record and its continuation will become extremely useful in validation and skill assessment of a variety of climate models being run. MOVE is represented via OceanSITES in the CLIVAR GSOP (Global Synthesis and Observation Panel) where just this cross-fertilization between sustained observations and climate models is being facilitated. Additionally, transport timeseries through long sections like MOVE may become an important constraint in assimilating climate models.

MOVE directly addresses and fulfils the OCO **program deliverable** "to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change". The observations from MOVE may be the first to detect changes since it is the longest existing record of direct thermohaline circulation transports.

The funding for MOVE does not allow for any scientific analyses, only the bare operations can be covered with the available budget. The future construction of indices of thermohaline circulation strength, and the cooperation with coupled climate modeling groups for initializing or constraining climate forecasts will require additional resources which do not currently exist due to insufficient funding. This may be a funding item for the future NOAA climate services.

MOVE is part of the global timeseries network OceanSITES, and thus contributes to the global ocean observing system. The data from MOVE are currently only retrieved once per year, i.e. in delayed mode. We are trying to work towards more real-time data delivery, but this can only be done in small incremental steps with the current funding level. After careful calibrations and quality control, all MOVE data become part of the OceanSITES data system, and are thus publicly available in a unified format for all outside users, from the central location for all the global timeseries data covered under the OceanSITES system (see www. Oceansites.org).

4. Education and Outreach

The MOVE project has high visibility on the Ocean Timeseries Group website at SIO (http://mooring.ucsd.edu). The MOVE approach and results are featured prominently in each year's introductory oceanography class at SIO (over 50 graduate students from all disciplines) and in each year's specialized class on observational techniques in oceanography, and always

attracts a lot of interest/attention from the students. Young graduate students (sometimes even new incoming ones) participate in each year's MOVE cruise, as both an inspirational and educational experience, and thus obtain intense insights into both the drivers and the approaches and techniques for sustained global ocean observations. Students working on MOVE related topics are also invited and encouraged to attend meetings, conferences, the NOAA Annual System Reviews, and participate actively where possible. In addition, one post-doctoral scholar at SIO is making critical contributions to the MOVE effort, and at the same time is being prepared to continue the mission of global ocean climate observations amoung the next generation of ocean researchers.

5. Publications and Reports

5.1. Publications by Principal Investigators

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