# MOVE

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## 1. 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, starting in the year 2000, by installing and sustaining an observing system for the lower branch (deep, cold return flow) of the overturning circulation in the Atlantic.

MOVE operates the circulation monitoring array in the subtropical West Atlantic along 16N, with the objective to observe the transport fluctuations in the North Atlantic Deep Water layer. 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 Mid-Atlantic Ridge. The geostrophic transport fluctuations through this section are determined using dynamic height and bottom pressure differences between the moorings. 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.

To date, the array has been collecting 13 years of temperature/salinity data (for relative geostrophic transports), 13 years of current meter data (for boundary slope transports), and 11 years of bottom pressure data (for barotropic transports, a data gap exists from 2005-2007). Due to the built-in redundancy, data are available from early 2000 until mid 2013. Interannual and long-term changes in the circulation and its vertical distribution are clearly visible now. Joint analyses with other arrays like RAPID, with projects in the Labrador Sea, and also with modeling teams are under way, in order to inter-relate the changes, assess the basin-scale significance of the data and understand the differences.

The MOVE array also contributes to closing one of the gaps in the sustained ocean climate observing system which was identified by the global community at OceanObs09: techniques and programs for monitoring the circulation and mass/heat/freshwater transports of major current

systems. For broad-scale and deep-reaching circulations, the MOVE approach of fixed-point horizontally integrating installations highly suitable. MOVE is one of the first sustained sites which are aimed at filling this gap in the global ocean observing system.

The supported activities include operation of three moorings and several bottom pressure sensors along 16N and processing of the data. This includes construction of moorings, execution of cruises, servicing and calibration of sensors with extreme accuracy, upgrading of technology, and participation in the OceanSITES effort.

The anticipated products and outcomes include:

- the longest record of transports in the southward branch of the Atlantic thermohaline circulation (AMOC)
- data sets to validate and constrain ocean circulation and coupled climate models
- integration of the data at this latitude with Atlantic-wide observing efforts via US-AMOC and international collaborations
- connections between observations at high latitudes (Labrador Sea) and the MOVE transports.

The users/applications include climate modelers and forecasters, climate impact studies, IPCC assessments, and the observational and modeling and data assimilation research community. The 2013 IPCC assessment showed the MOVE transport timeseries.

## 2. Scientific and Observing System Accomplishments

### a) Field Work

FY13 funds were used to build and test instruments and moorings for the May 2013 Meteor cruise with a full deployment of all moorings and PIES. Containers were shipped to Guadeloupe, where we also retrieved our remaining mooring gear still stored there since the May 2011 recovery (due in insufficient funds for shipping back to San Diego). We sent 4 participants on the Meteor cruise, and they worked with the German team to recover the three existing MOVE moorings, calibrate all microcats via CTD casts, and re-deploy three new moorings. The existing PIES from December 2010 were left in place and were doubled-up with two new PIES (one at each end point of the section), in order to finally implement our scheme of 4-year deployments of dual PIES which overlap by about 2 years each (to remove sensor drift better). There was not sufficient time to experiment with downloading data (from the older PIES) acoustically since the intensive mooring and calibration work took all available time and energy of the team. The Meteor cruise ended in the Cape Verde Islands, from where containers were shipped back to San Diego.

All recovered instruments delivered good data. We thus have over 13 years of continuous density and current meter data, allowing calculation of baroclinic plus boundary transports for this period. The data return rate has been over 98% over 13 years, which has established a truly unique data set.

At the time of writing, staff from our team is participating in the NTAS/MOVE cruise on the NOAA ship “Ronald Brown” in order to check on health of the moorings and acoustically download data. Data from all instruments (T/S sensors, current meters, PIES) could be retrieved except from the nearly 3-year old PIES at the offshore site M1 (the modem battery appeared to

be dead, but the PIES was there and functioning as confirmed by acoustic commands directly to it). These data are now extending our MOVE timeseries by another 6 months to nearly 14 years.

### b) Scientific Analyses

In previous reports, our GRL publication, and many presentations, we had speculated that the weakening trend we had found over the first 9 years of MOVE was part of decadal natural variability. As such, a renewed increase was to be expected at some point. Our new data now seem to suggest the presence of such changes. Figure 1 shows the internal (baroclinic, sheared) plus boundary current transport of the North Atlantic Deep Water (NADW) layer until May 2013, note that all values are negative (southward). The first 6-8 years, the decrease in transport is visible, but in the last 4-6 years a clear increase emerges. This is the first such observation, and we are in the process of further analyzing its robustness and detailed properties.

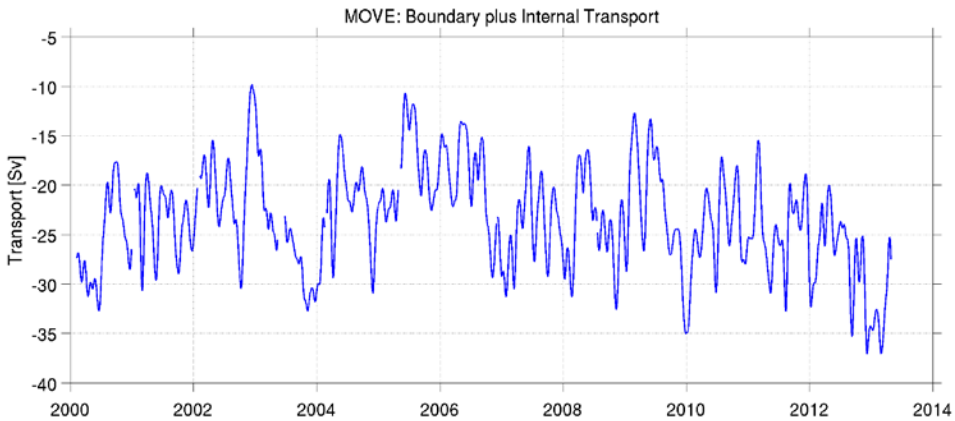
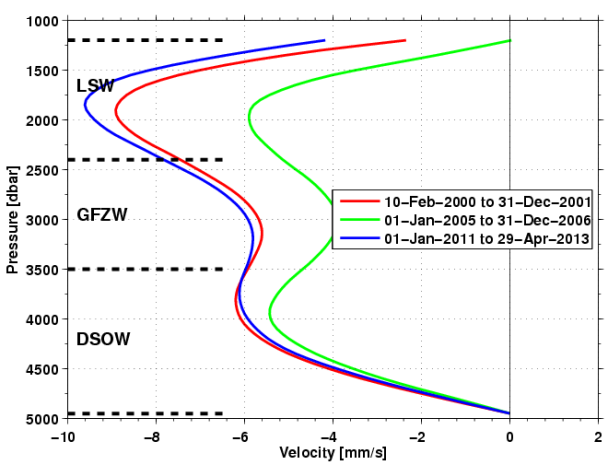



***Figure 1**: NADW transports (negative southward) over 13 years from sheared geostrophic flow relative 4950db and the boundary flow measured with current meters.*

Mean flow profiles from the early, middle, and late phases suggest that much of the transport change is found in the Labrador Sea Water (LSW) layer, between 1200m and 2800m, but the density trend profiles show that the recent changes are found throughout the water column, see figure 2.



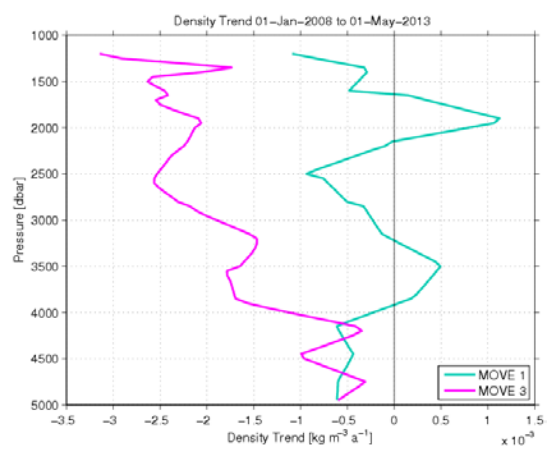



***Figure 2**: Left - Mean flow of profiles of the first 2 years (red), the middle 2 years (green) and the last 2 years (blue), showing the weakening and renewed strengthening of the southward flow especially in the LSW layer. Right – trends of density over the last 5 years at the western mooring (MOVE3, magenta) and the eastern moorig (MOVE1, cyan).*

While the transport decrease over the first half of the MOVE period was related mainly to changes near the mid-Atlantic Ridge (mooring MOVE1), the new increase is clearly caused by density and dynamic height changes at the western boundary (figure 2 right, and other analyses document this).

We have extended our collaborations with the observational and modeling groups in Kiel, partly to study potential connections of the variability observed in MOVE with water mass changes in the Labrador Sea (LS) and at its exit. It is widely believed, and reproduced in many model simulations, that an MOC reduction such as observed in MOVE since 2000, is consistent the reduced LSW formation and LSW density decreases since the mid-nineties. However, a reduction in the warming/density decrease is visible since 2004/05 in the central LS and since 2008 at the exit (possibly even a stagnation there), see figure 3 (left). Interestingly, and this is a somewhat novel result by our Kiel colleagues, the density in the deep branch of the NADW (the "overflow water") at the exit of the LS, seems to have been getting denser all the time (figure 3 right). This means that there have been changes in the Labrador Sea region which might be related also to increases in the MOC at lower latitudes ?

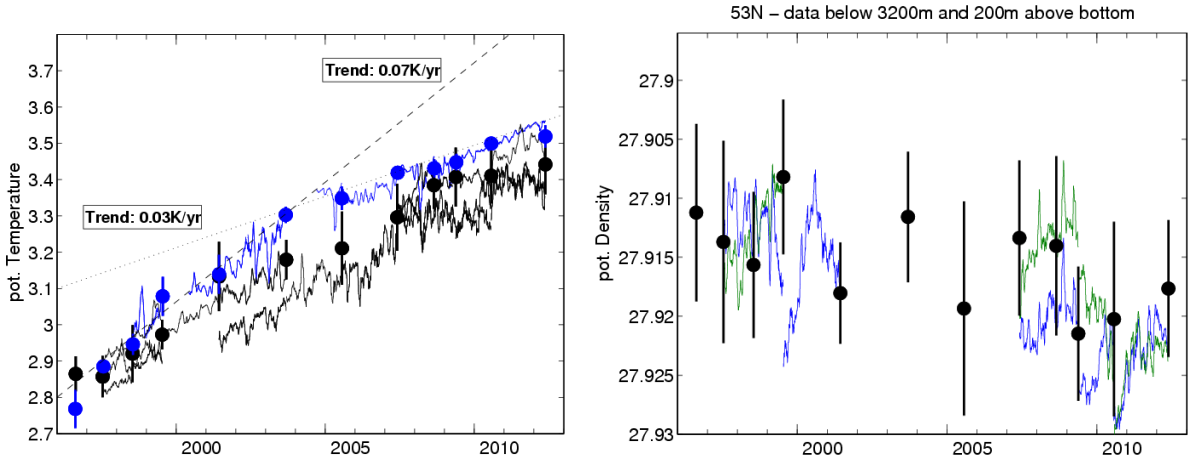



***Figure 3:** Left – temperature changes of LSW in the central Labrador Sea (blue) and at its exit near 53N (black). Right – density changes in the deep NADW at the exit of the Labrador Sea, note inverted density scale. In both panels, continuous traces are from mooring data, and circles with standard deviation bars are from ship observations. All data from J.Karstensen and J.Fischer from Geomar/Kiel.*

These are topics of ongoing analyses and collaborations, also with the modeling teams at Geomar. The Kiel ORCA model will be jointly analyzed to compare variability in MOVE and RAPID, to distinguish thermohaline and wind forcing, and to analyze spreading paths for anomalies from the Labrador Sea to the MOVE region. Some of these joint studies between the MOVE project and the Geomar observational and modeling groups will be presented at the ASLO/AGU Ocean Sciences Meeting in 2014.

We have also initiated collaborations with J.McClean at SIO who runs very high resolution coupled climate models, in addition to global forced ocean-only models (with sea ice). MOVE data will help to validate and ultimately improve her model hierarchy.

Apart from these individual national and international collaborations, we participate actively in US AMOC, international AMOC, and in OceanSITES. Due to cruise constraints, we could not join the 2013 US AMOC meeting, but we will make a point to re-introduce MOVE results and data into the AMOC community at the 2014 meetings.

**c) Data Management**

We routinely quality-control the mooring data (CTD and current meters) and provide it to OceanSITES as delayed-mode data within a few months after recovery of the instruments. All of these data have been provided as of late Oct. 2013.

Work on the PIES data is ongoing. There are two issues w.r.t. data management surrounding PIES:
(1) It is not absolutely clear what processing steps should be done to these data in order to arrive at a "final" data version.

(2) There are missing naming conventions for the parameters measured, which have been requested from the CF metadata group, but not yet been received.

Item (2) is a technical issue that should be resolved within a few weeks to months. Item (1) has implications for the scientific usefulness of the data for particular purposes and is therefore harder to bring to conclusion. We are pursuing the following approach: to distribute the parsed raw data with complete metadata information in an OceanSITES-compliant format, and as ancillary datasets to include one or more processed versions (filtered data from our own science analyses) with proper documentation. The technical details of how to separate the multiple data versions in a single file have been resolved.

**Summary Information:**

a. <u>Project deliverables serving the observing system's program deliverables and priorities</u>
One program deliverable is to identify changes in the thermohaline circulation, the related Climate Goal is vulnerability to climate extremes

- MOVE provides the longest directly observed timeseries of the strength of the southward limb of the AMOC
- MOVE is the first to show decadal variability in the AMOC strength and vertical structure
- MOVE allows addressing the relation between NADW variability at different latitudes and assessment of meridional coherence

b. <u>Achievements during FY2013</u>

- Field work to swap out all moorings and to double-up the remaining PIES
- First substantial acoustic download of data from moorings and PIES deployed in MOVE
- First indications of renewed AMOC strengthening after a decade of weakening
- Potential relations between MOVE decadal variability and changes in the Labrador Sea

c. <u>Scientific advances made and/or facilitated through the project activities</u>

- Observational proof of interannual and decadal-scale variability in southward AMOC flow
- Ongoing studies about meridional coherence and forcing based on observational data
- Validation of circulation and climate models with the observational MOC data

d. Significance of these advances

- Knowledge of the existence and sense of AMOC changes will allow climate forecasts (direct utility for Program Climate Goal)
- Circulation and climate models can be tested/validated
- Comparing MOC observations at several latitudes and with models will allow design of better future observing systems

e. Information jeopardized due to a lack of funding, lack of instrumentation, or inability to carry out the work

- Funding is insufficient for more active engagement with the AMOC and modeling communities. Data management is still behind and lacking funding.
- The new moorings have inductive communication and acoustic modems, so we could download the data more regularly by deploying gliders and using the technology developed in CORC, but we do not have the funds available for glider operations in MOVE.

f. Web sites for the program

- http://mooring.ucsd.edu/MOVE

g. Data Management

The project is presently not collecting real-time data, so this does not apply. Telemetered data which are received through the acoustic communication paths will be made available via OceanSITES once the data are collected (a field expedition is underway as of late Oct. 2013 to retrieve subsets of data). Exception: OceanSITES data formats for PIES instruments are still not functional, so these data are presently not distributed. OceanSITES is working the issue, together with the "CF" metadata conventions group.

Once collected, the data will reside in an institutional server with a backup, as well as the OceanSITES data centers. The data will be publicly available on OceanSITES. Note exception for PIES data above.

Data reside in an institutional server with a backup, as well as the OceanSITES data centers. The data are publicly available on OceanSITES. Data are available through spring 2013. Note exception for PIES data

New data are fed into the systems as they become available, which is approximately yearly.
The backup of the institutional server is run daily. The access points at OceanSITES presently serve as archives. There are two such "global data access centers" (GDACs), which mirror each other at least daily. A permanent archive from OceanSITES to a facility at NOAA NODC is under development.

The two OceanSITES GDACs for data access are:
ftp://data.ndbc.noaa.gov/data/oceansites/DATA/
ftp://ftp.ifremer.fr/ifremer/oceansites/DATA/
The project maintains an institutional website at:
http://mooring.ucsd.edu/MOVE

We can retrieve our own data from the OceanSITES GDACs.

The project adheres to the CLIVAR data policy found at:

http://www.clivar.org/resources/data/clivar-data-policy
The items under this policy, implemented by using the OceanSITES systems, serve as the data management plan of the project.

## 3. Outreach and Education

MOVE is regularly presented to the next generation of researchers at the national and international AMOC and RAPID meetings. These events are heavily attended by students and post-docs. MOVE is communicated to the public via various websites (see above).

One young scientist and one graduate student were partially supported by MOVE. Wherever possible, we invite students to participate in MOVE cruises. One student (Samuel Wilson) joined the recent Meteor MOVE cruise. Incoming new students at SIO sometimes spend the first summer in our lab, and MOVE is one the projects they are exposed to and sometimes help with data processing for. In my teaching, and during visits of prospective students, MOVE is used as a demonstration of exciting and relevant research.

## 4. Publications and Reports

### *4.1. Publications by Principal Investigators*

Lankhorst, M. and H.-J. Kim (2012): Comparing Automatic versus Human-Created QC Flags of Oceanographic Mooring Data and Applicability to the OOI. 2012 Ocean Sciences Meeting, Salt Lake City, UT. American Geophysical Union [and others], Conference Proceedings.

M. Srokosz, M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke, and R. Sutton (2012): Past, Present, and Future Changes in the Atlantic Meridional Overturning Circulation. Bulletin of the American Meteorological Society, vol. 93, pages 1663–1676. doi:10.1175/BAMS-D-11-00151.1.

M. O. Baringer, S. A. Cunningham, C. S. Meinen, S. Garzoli, J. Willis, M. Lankhorst, A. Macdonald, U. Send, W. R. Hobbs, E. Frajka-Williams, T. O. Kanzow, D. Rayner, W. E. Johns, and J. Marotzke (2012): Meridional overturning circulation observations in the subtropical North Atlantic [in "State of the Climate in 2011", chapter "Global Oceans"]. Bulletin of the American Meteorological Society, 93 (7), S78-S81.

M. O. Baringer, W. E. Johns, G. McCarthy, J. Willis, S. Garzoli, M. Lankhorst, C. S. Meinen,U. Send, W. R. Hobbs, S. A. Cunningham, D. Rayner, D. A. Smeed, T. O. Kanzow, P. Heimbach,E. Frajka-Williams, A. Macdonald, S. Dong, and J. Marotzke (2013): Meridional overturning circulation and heat transport observations in the Atlantic Ocean [in "State of the Climate in 2012", chapter "Global Oceans"]. Bulletin of the American Meteorological Society, 94 (8), Aug. 2013, S65-S68.

### *4.2. Other Relevant Publications*

IPCC, 2013: Climate Change 2013: The Physical Science Basis. IPCC, Geneva. (http://www.climatechange2013.org/report/)