Meridional Overturning Variability Experiment (MOVE)

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Table of Contents

Project Summary... 1
2. Scientific and Observing System Accomplishments.. 2
2.1. Outreach and Education.. 6
MOVE was presented to the next generation of researchers at the WCRP conference in Denver via a poster. MOVE is communicated to the public via various websites (see above). 6
3. Publications and Reports 6
3.1. Publications by Principal Investigators 6
4. Figures 7

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 Midatlantic 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 delivered 430 sensor-years of temperature/salinity data, 154 sensor-years of current meter data, and 34 sensor-years of bottom pressure data. Due to the built-in redundancy, transports are available now for the complete project period (nearly 11 years) since initiation of the program. Interannual and long-term changes in the circulation and its vertical distribution are starting to be visible. Joint analyses with other arrays like RAPID and also with modeling teams are under way, in order to assess the basin-scale significance of the data and understand 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 is promising. 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:

- long records of the deep transports in the southward branch of the Atlantic thermohaline circulation (AMOC) at this latitude
- data sets to validate and constrain circulation and climate models
- integration of the data at this latitude with Atlantic-wide observing efforts via US-AMOC and international collaborations.

The users/applications include climate modelers and forecasters, climate impact studies, IPCC assessments, and the observational and modeling and data assimilation research community.

2. Scientific and Observing System Accomplishments

a) Field Work

As already partially addressed in the previous progress report, a minimal amount of ship time for MOVE work was made available during the RV Ron Brown cruise in December 2010, after initially the MOVE project had slipped from the ship schedule altogether. During those hours which were freed up on that cruise, moorings M1 and M3 were recovered with all instruments intact and data recorded, moorings M1, M3, M4 were deployed with the new inductive/acoustic communication capability, calibration CTD casts were carried out for the microcat instruments, new PIES were deployed at M1 and M3, and data from the existing PIES at the same locations were transferred with the built-in method of encoding daily-average readings by time-delay between pings.

The schedule did not allow another 4 hours to recover the simple and much shorter mooring M4 which had been in the water for over 2 years, even though the ship was at the site. Since it was urgent to recover that mooring, a very expensive separate trip with a small contracted boat had to be organized out of Guadeloupe, and was executed in May 2011. Just the shipping, boat cost, travel expenses were close to $25,000 and many man-weeks of labor were incurred for the preparation, execution, and reception of gear, none of which were ever in our budget. We estimate the total unplanned expense of this operation to be in the neighborhood of $45,000 which is hard to accept given that it could have been done in 4 hours on the NOAA ship which was right there. We still have gear in Guadeloupe which we cannot bring back to San Diego at a reasonable cost, since the only option that the shippers can find is to either fly everything for $6500 or send a complete container at even higher cost. Figure 1 shows a photo of the boat which was used for 2 days to do the work.

After the remaining mooring M4 was successfully recovered, we had a complete data set in hand for extending transport timeseries of southward North Atlantic Deep Water (NADW) flow.

During December 2011, a new Ron Brown cruise took place for mainly NTAS work. Since our MOVE moorings are now designed for 2-year deployments, no mooring activity was required. However, two aging PIES (bottom pressure sensors/inverted echosounders) were recovered after 4.5 years in the water, for which we sent a technician from SIO (P.Chua) to participate in that cruise. A third PIES which also is getting old could not be recovered due to diplomatic clearance issues (in French waters) – for this PIES we have to rely on data downloaded acoustically during the December 2010 cruise, but since this instrument series had a firmware bug (now fixed by manufacturer URI) the time stamp of the data is uncertain which makes for more noisy barotropic transport estimates (see below).

b) Scientific Analyses

Much of our effort was dedicated to getting the previous 9.5 years of data published, which had showed the weakening of the southward flow by 20% (see last year's report). Reviewers wanted to see significant additional work addressing our assumptions of a constant reference level for the geostrophic transports on long time scales, and also for the validity of observing only the western basin of the Atlantic at 16N. For this, a hierarchy of model analyses was performed, mainly in order to test how the NADW transports in models change when a fixed reference level is used versus the full model transports. The final figure used in the Supplementary Material for the publication in Geophysical Research Letters (GRL) is reproduced here in figure 2. The article finally appeared in print in December 2011 in GRL, and since then has got some attention and compliments by colleagues, including recognition and special mention in

- a research highlight in the journal Nature Climate Change
  (http://dx.doi.org/10.1038/nclimate1362)
- a GRL editor's highlight (http://www.agu.org/cgi-
  bin/highlights/highlights.cgi?action=show&doi=10.102/2011GL049801jc=gl)
- an AGU press release journal highlight
  (http://www.agu.org/news/press/jhighlight_archives/2012/2012-01-13.shtml#one)
- an EOS "research spotlight" story (coming).

The main figure from this GRL article will also be used in the next IPCC assessment report.

Further, analysis effort was expended on the new longer record in hand with the recent recoveries. The microcat records from moorings M1/M3, and the current meter data from M4/M4 were quality-controlled, had calibrations applied, and were processed to yield another 1.5 years of internal-plus-boundary transport in the NADW layer. The new extended timeseries is shown in figure 3. A large event increased the southward transport at the end of 2009/beginning of 2010. With this, our previous weakening trend is not significant anymore, which we tentatively interpret as either a temporary anomaly (in which case the trend would resume in future years) or the beginning of the decadal cycle switching from weakening to strengthening. We are currently comparing this with RAPID transports, where at exactly the same time an opposite signal was found, which now makes the RAPID timeseries have a significant decreasing trend. This is an exciting challenge which we are actively pursuing jointly with RAPID scientists, especially T.Kanzow in Kiel/Germany. For the barotropic bottom-pressure derived transports we have data for the same time period, but after Jan 2010 these data are more noisy due to the time stamp bug (see above), shown in figure 4.

For completeness, in figure 5 an extended version of the annual mean flow profile (or transport per depth) figure is shown, now with two additional years. The large variability in the vertical structure, which is free of any assumptions, had impressed several reviewers of our GRL paper. A similar figure was prepared by E.Frajka-Williams using RAPID data, and confusingly there an increase in southward flow is found in 2010, similar to our figure (however, she only calculated internally referenced transports like we do in MOVE, while the normal RAPID analyses which show a decrease use absolute flows determined from mass conservation).

We continue to collaborate with RAPID and modeling teams in order to
- assess the robustness and representativeness of the MOVE results
- look for meridional coherence and propagation in NADW and MOC flow changes
- relate changes observed to forcing, e.g. water mass changes at higher latitudes
- test to what degrees models agree with our observations
- help modeling teams to constrain or initialize their models with our observations.

Some initial attempts along those lines are also reproduced in the following figures. Figure 6 shows a rough comparison from last summer to overlay MOVE and RAPID transports. There appears to be some coherence with a time lag of 50 days. We are continueing to investigate this. Figure 7 shows an analysis of 8-yr moving transport trends at 16N in a number of assimilating model outputs that we had got from Tony Lee at JPL, in comparison with the MOVE trend until 2009. Several models appear to have decadal or multi-decadal oscillations, and are in a weakening phase since about 2000 like MOVE, with magnitudes similar to the MOVE observation. Figure 8 shows a “sensitivity analysis” from the Kiel ORCA circulation model (no data assimilation, but carefully selected forcing fields). The NADW transport changes due to variability in the thermohaline forcing shows multi-decadal variability with a weakening phase since about 1995, qualitatively consistent with the MOVE results.

Apart from these individual national and international collaborations, we participate actively in US AMOC, international AMOC, and in OceanSITES.

c) Data Management

Within the available resources we make a best effort at quality controlling the MOVE data set and providing it to OceanSITES. The complete set of microcat data since 2000 has finally been re-processed to make sure it is of uniform quality, and is now available in OceanSITES format via OceanSITES. The current meter data from the M3/M4 (and earlier also M5) moorings were re-processed during 2011 and seem to be in good shape now. With these current meter data, the skill and required linear combinations with the now reduced array using only 4 current meters was repeated and confirmed, figure 9 shows the result. Submission to OceanSITES is planned. The bottom pressure and inverted echosounder data will take more time, since this is also a complicated data set, and we would like to learn more from the now overlapping and staggered side-by-side deployments of PIES. We hope to be able to work on that data set in more depth in the coming year.

Summary Information:

a. Project deliverables serving the observing system’s program deliverables
- Longest directly observed timeseries of the strength of the southward limb of the AMOC

- Quantification of variability in the AMOC strength and vertical structure
- Relation between NADW variability at 16N and at other latitudes / assessment of meridional coherence

b. Achievements during FY2011

- Our 9.5year long timeseries showing a weakening in the southward flow passed peer review and was published in GRL
- Multiple field work to recover and redeploy moorings and PIES
- Newly recovered instruments and their data extend the length of timeseries to nearly 11 years
- Initial comparisons of MOVE results with RAPID and model outputs

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

- Observational proof of interannual and decadal-scale variability in southward AMOC flow
- First studies will be enabled about meridional coherence based on observational data
- Developments will be enabled to constrain or initialize 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
- 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

- Due to the IDC rate change at SIO and due to the unexpected expenses to compensate for the lack of NOAA shiptime (by staging another local cruise out of Guadeloupe), we are very short of funds and cannot carry out analysis work at the rate that would be desirable/needed.
- 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.
- Data management is far behind and lacking funding, especially the QC and dissemination of bottom pressure data has not been possible yet.

f. Web sites for the program

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

g. Data Management

- Data not distributed on GTS since not in real-time
- Delayed-mode data is on institutional computer with backup system, plots are provided on the website. Processed data are made available through OceanSITES ftp servers up to most recent field operations and this implemented for microcat (T/S) and current meter data so far.
- Archival on institutional backup system happens daily; transfer of newly processed data to OceanSITES repository approx yearly.
- Data plots are shown on http://mooring.ucsd.edu/MOVE

2.1. Outreach and Education

MOVE was presented to the next generation of researchers at the WCRP conference in Denver via a poster. MOVE is communicated to the public via various websites (see above).

In summer 2011, two new incoming SIO students have participated in MOVE model analyses, and this was their first introduction to actual ongoing research. One postdocs and one graduate student were partially supported by MOVE. Wherever possible, we invite students to participate in MOVE cruises. In my teaching, and during visits of prospective students, MOVE is used as a demonstration of exciting and relevant research.

3. Publications and Reports

3.1. Publications by Principal Investigators

Send, U., M. Lankhorst, and T. Kanzow (2011) : Observation of decadal change in the Atlantic Meridional Overturning Circulation using 10 years of continuous transport data. Geophysical Research Letters, 38, L24606, doi:10.1029/2011GL049801

4. Figures

Figure 1: *The boat in Guadeloupe which was contracted for the recovery of the current meter mooring M4.*

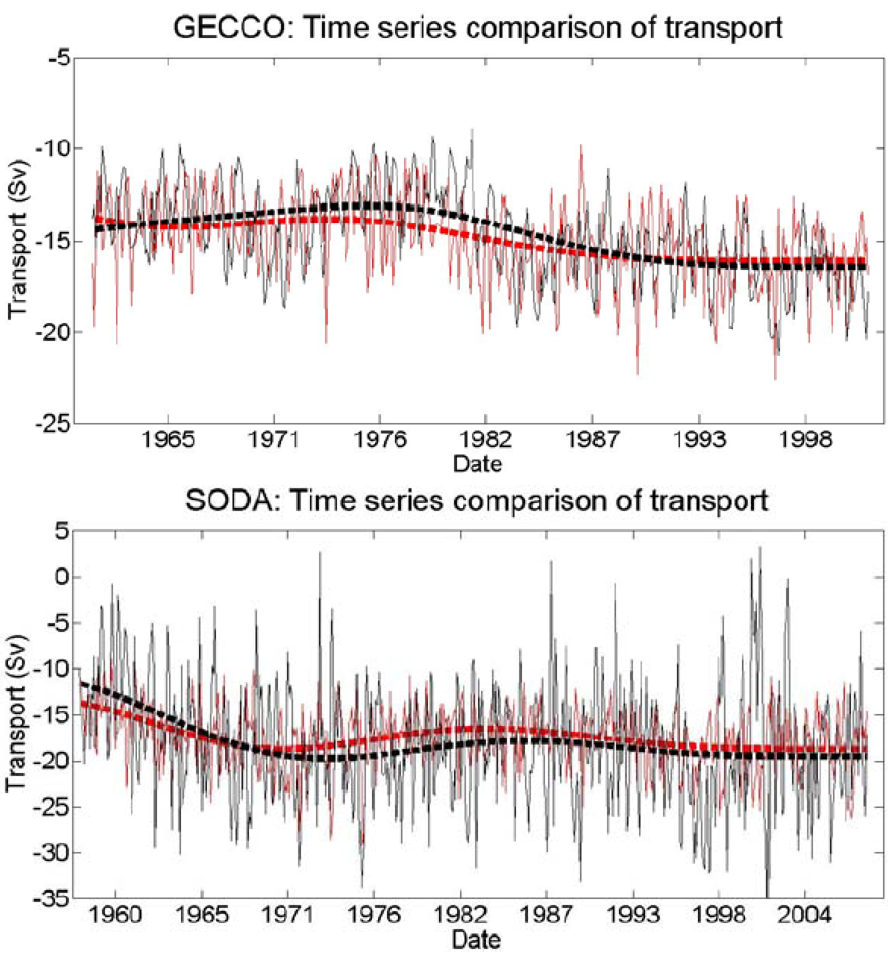

Figure 2: *MOC overturning transport at 16N in the GECCO (top) and SODA (bottom) models, monthly (thin) and with a 20-year filter (thick). Red is the original transport (with barotropic flow at reference level, i.e. a fluctuating level-of-no-motion), black is result with fixed reference level at the depth where the mean flow has its zero crossing. The trends on 10-year timescales are similar.*

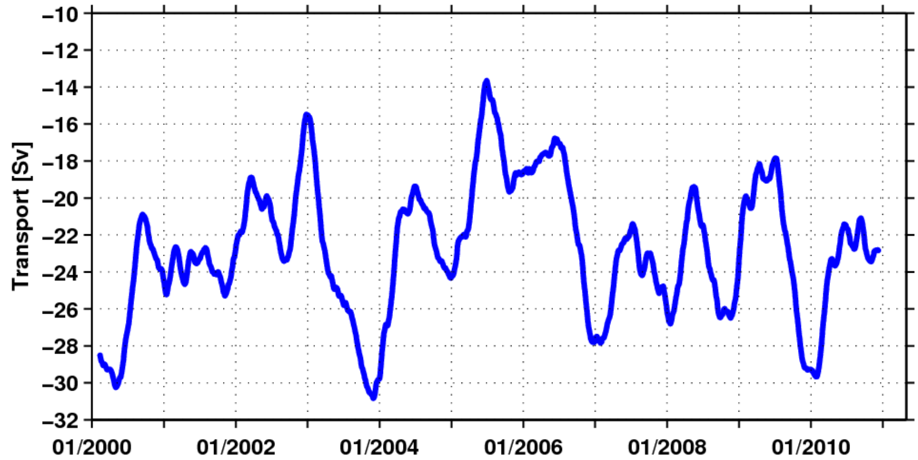

Figure 3: New extended timeseries of NADW transport from the internal geostrophic component (referenced to 4900m) plus the boundary current component.

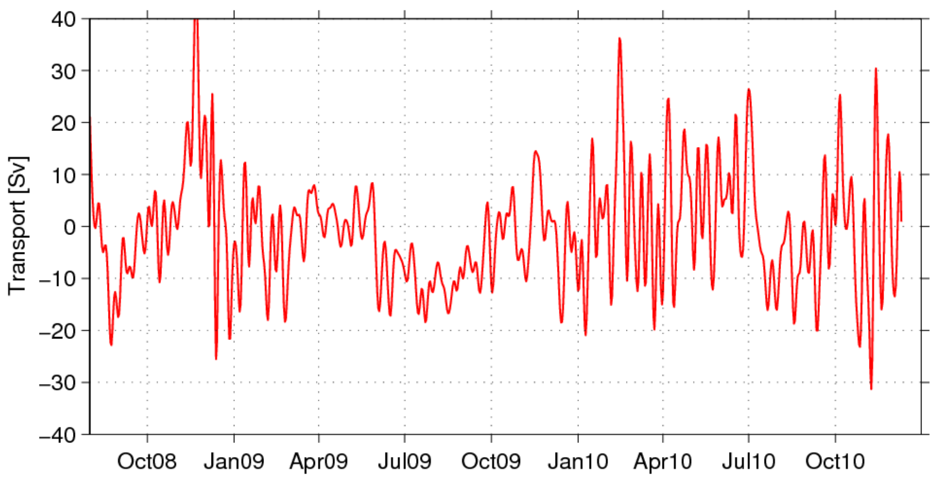

Figure 4: Barotropic transport derived from the bottom pressure (PIES) data, showing increased noise starting in Jan 2010 due to the URI time stamp bug in the acoustically downloaded data.

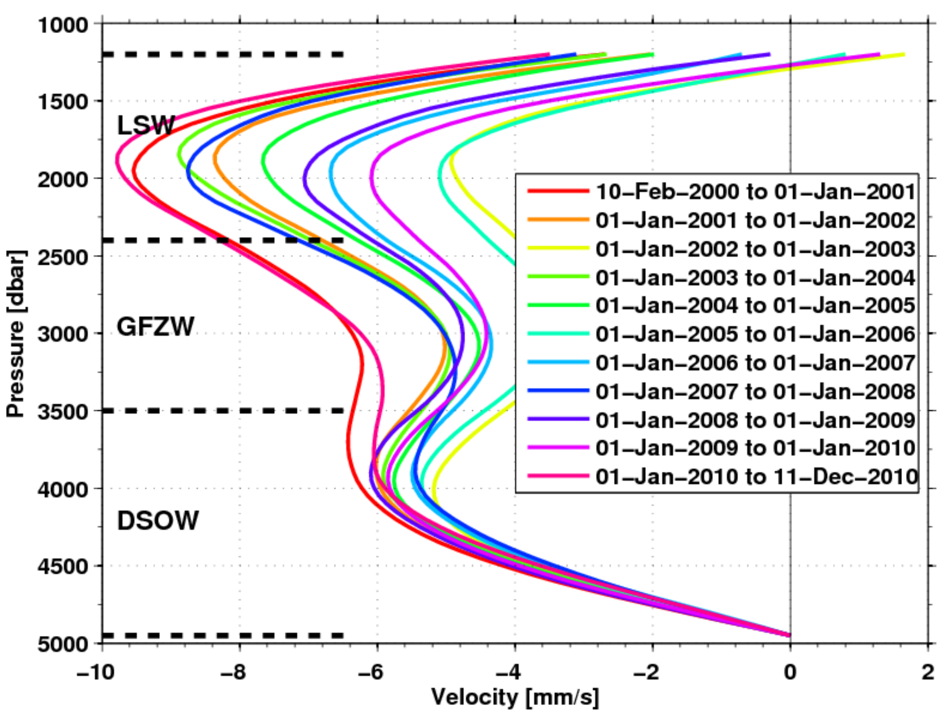

Figure 5: Annual mean profiles of geostrophic transports relative to 4950db. Large changes in amplitude and structure of the NADW flow can be seen year to year.

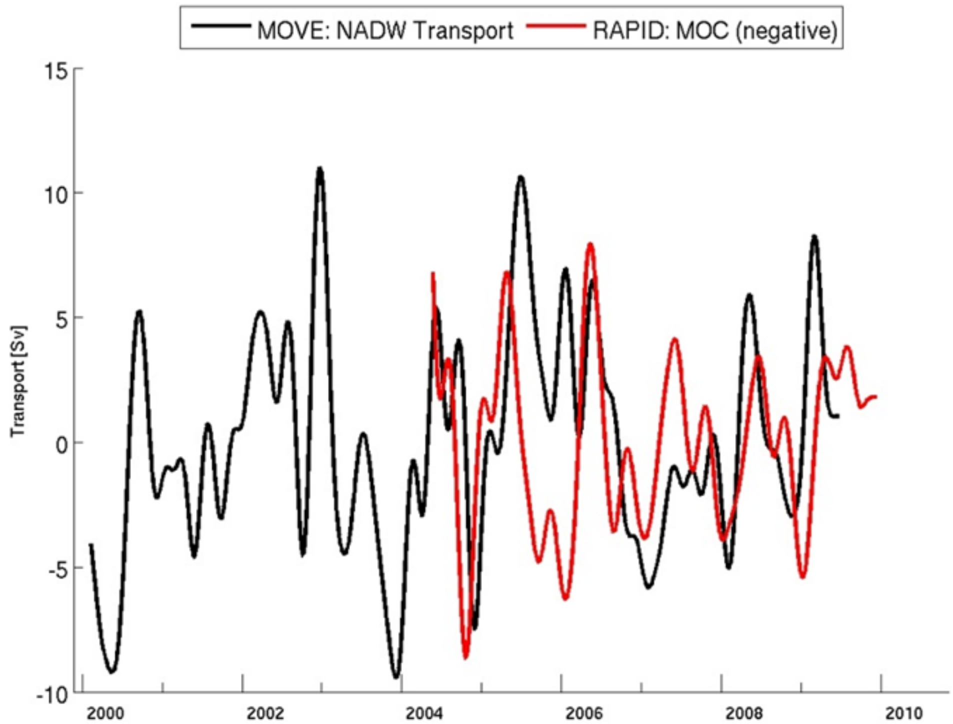

Figure 6: *Comparison of RAPID MOC time series with NADW transport from MOVE. The RAPID MOC time series has been shifted forward by 50 days. This shift would suggest a signal propagation speed of ~20 cm/s.*

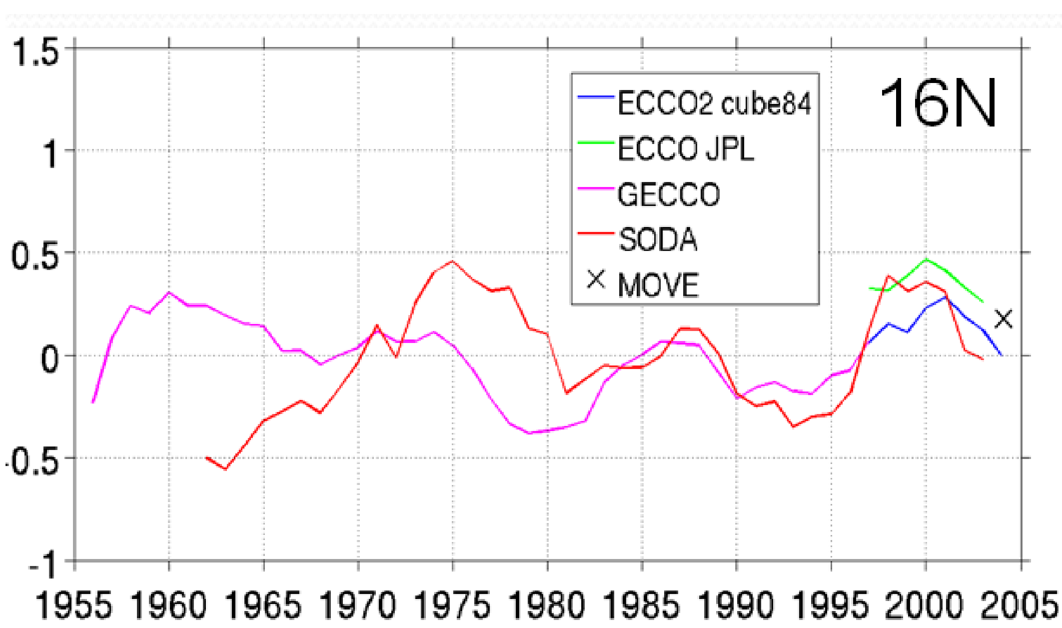

Figure 7: *Transport trends over 8-year gliding time windows in a number of models, compared to the MOVE trend until 2009.*

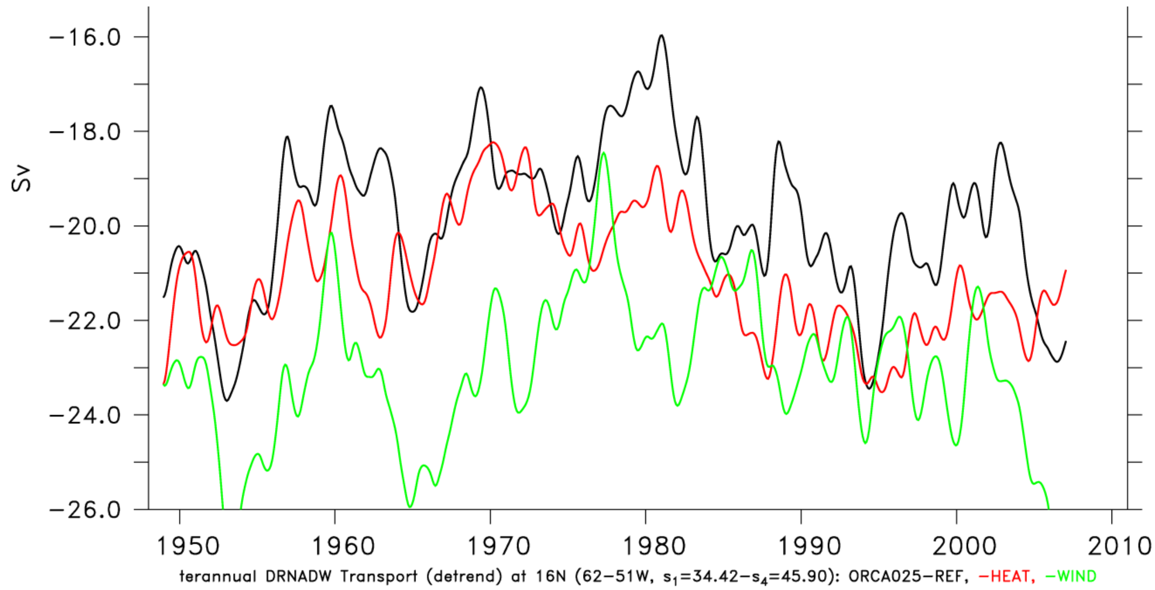

Figure 8: *Kiel ORCA model analysis of the NADW transport at 16N and over the western basin section as in MOVE, showing the full transport in black, the component only due to thermohaline forcing (mainly Labrador Sea convection) in red, and the component only due to wind variability in green.*

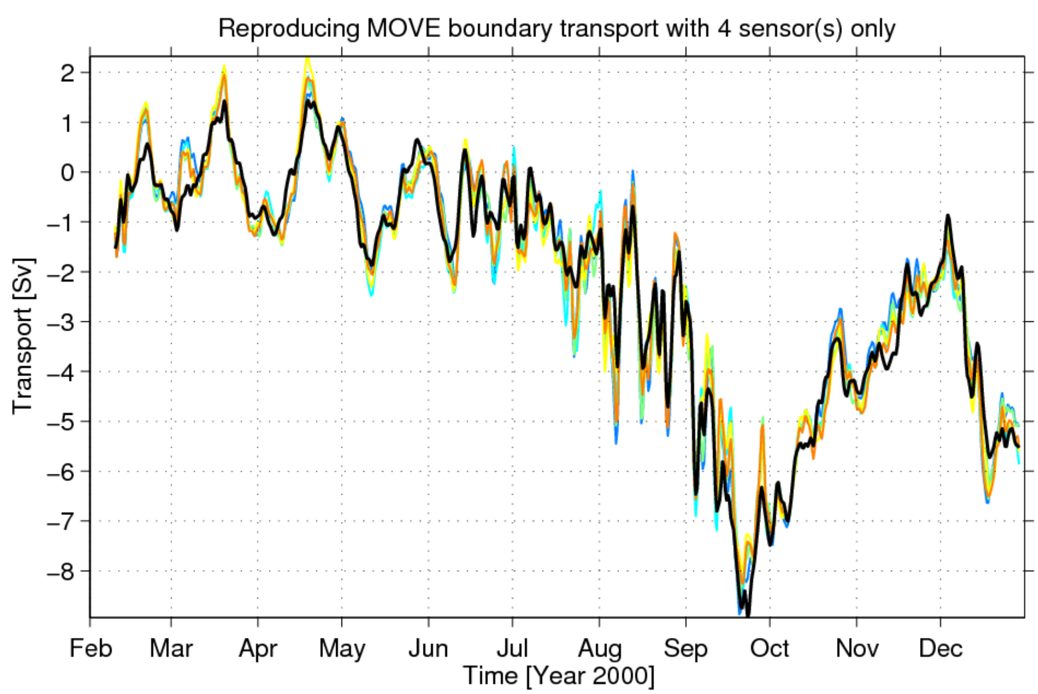

Figure 9: *The black line shows the boundary triangle transport over the continental slope from the initial intensive array of current meters on three moorings (M3, M4, M5). The colored lines show the simulated best fit to this using different geometries of four current meters on just M3 and M4. The best of these is what we now use in our reduced array.*