Progress Report:
Meridional Overturning Variability Experiment (MOVE)

Period of Activity: 01 July 2021 – 30 June 2022

Principal Investigator
Uwe Send
Scripps Institution of Oceanography
9500 Gilman Drive #0230
La Jolla, CA 92093-0230
Email: usend@ucsd.edu
Tel: (858) 822 6710

Financial Contact
April Fink
CIMEAS / Scripps Institution of Oceanography
9500 Gilman Drive #0234
La Jolla, CA 92093-0234
Email: afink@ucsd.edu
Tel: (858) 534 1876

Signature Date

Signature Date

Co-Principal Investigator
Matthias Lankhorst
Scripps Institution of Oceanography
9500 Gilman Drive #0230
La Jolla, CA 92093-0230

Budget Summary
FY 2022: $539,016

MOVE: Meridional Overturning Variability Experiment

Uwe Send and Matthias Lankhorst
Scripps Institution of Oceanography, La Jolla, CA

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1. Project Summary

The meridional overturning circulation (MOC) in the Atlantic Ocean is one of the major oceanic climate drivers, with demonstrated impacts and control on climate in the northern hemisphere and globally. Variations in this circulation and the associated heat transport, both due to natural and man-made effects, are of utmost importance but have been impossible to observe directly until recently. 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 Atlantic MOC. This flow ultimately balances the warm MOC surface flow of the Gulf Stream and associated currents.

MOVE operates a monitoring array in the West Atlantic along 16°N, with the objective to observe the transport fluctuations in the North Atlantic Deep Water (NADW, 1200-5000m) layer. Three sites between the Lesser Antilles (Guadeloupe) and the Mid-Atlantic Ridge are occupied with moorings (figure 1). The MOC fluctuations across this section are determined as the sum of three components: a “boundary” part observed with current meters at the two western sites, an “internal” part based on density (temperature and salinity) measurements on the two eastern sites, and an “external” part from seafloor pressure at the two eastern sites. 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. MOVE activities include construction of moorings and deploying and recovering them, servicing and calibration of sensors with extreme accuracy, producing data products and scientific analyses, and participation in the international OceanSITES program. The data collected by MOVE are made freely available through the OceanSITES data portals. The scientific data products and outcomes of MOVE include:

- a record of the MOC strength that quantifies variability of this particular climate signal on time scales from seasonal to decadal periods
- 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

The users/applications of MOVE data 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, as do several recent annual "State of the Climate" reports in the Bulletin of the American Meteorological Society.

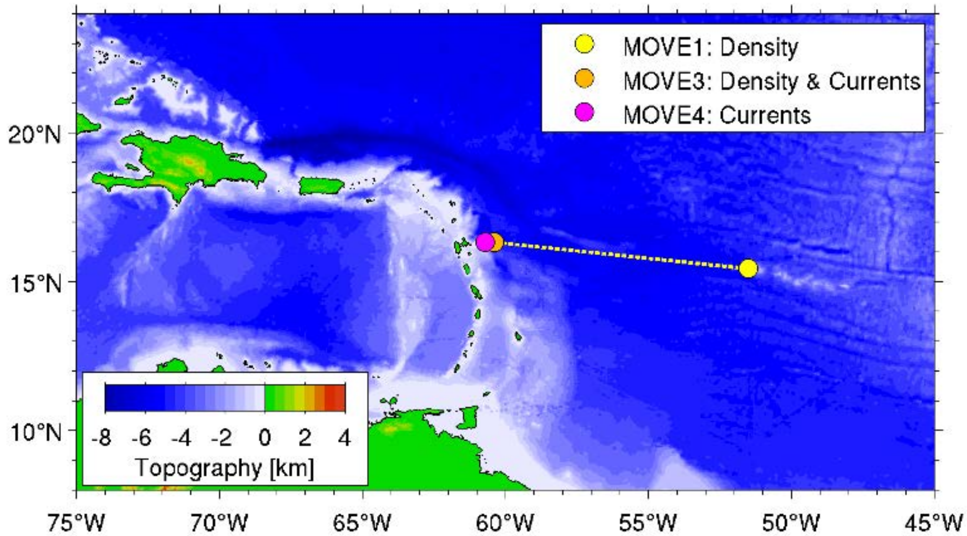

Figure 1: Map of the MOVE array (after Send et al., 2011). Each site is occupied by one mooring, and in addition, MOVE1 and MOVE3 each have two seafloor instruments called PIES (pressure-sensing inverted echo sounders).

2. Scientific and Observing System Accomplishments

Similar to previous years, the MOVE work plan set the following goals as performance measures, and **all goals were met or exceeded**:

- 3 moorings and 4 PIES instruments should be maintained in an operational status. This was accomplished - all relevant instruments were deployed prior to the present reporting period, and operated nominally throughout.
- 2 datasets (counting 1 per data type and per deployment period) should be processed, and 1 delivered to the OceanSITES data center for dissemination. In the present reporting period, there were no new datasets to be processed. Instead, the temperature and salinity data from all 14 previous deployments were reprocessed for better calibration accuracy, and all were uploaded to the OceanSITES data center.
- 1 conference presentation should be given, and this was done at the 2022 US AMOC Science Team Meeting in Woods Hole, MA, in April ("Atlantic Meridional Overturning Circulation Observed at 16N" by M. Lankhorst, J. Koelling, and U. Send). A minor

contribution was made to another presentation at the same meeting ("An Overview of The U.S. AMOC Science Team: Accomplishments and Challenges" by G. Danabasoglu).
- 1 publication should be produced. The actual number accomplished was 2 publications: Volkov et al. (2021) report on the state of the MOC in 2020 in the annual "State of the Climate" report, and Berx et al. (2021) present a brief overview of Atlantic observing systems for climate.

Substantial effort was spent during the present reporting period to prepare for a research cruise that occurred shortly thereafter, in October 2022, and successfully swapped the mooring array. During the preparation phase, hardware was purchased and assembled, and work plans were generated. A recurring issue during the preparations, encountered in previous as well as the present reporting periods, was that the ship schedule was not finalized in time. This leads to inefficiencies because plans have to be made and changed multiple times, and uncertainties because staffing plans and permit applications to work in foreign EEZ waters cannot be made reliably. In the present case, firm cruise dates and ports were only available 1-2 months before the cruise. With such short notice, staffing and vacation plans are adversely affected. In addition, applying for the foreign EEZ clearance is a process that needs to start 8-9 months ahead of time and requires a detailed list of ports, cruise dates, and staff - information that was not available in time and could only be provided by initial guesswork and subsequent corrections. This is inefficient and frustrating for the people who are involved in the work. The MOVE team feels that **NOAA needs to provide ship schedules in a more timely manner, and with fewer lingering uncertainties**.

The most notable observing achievement during the present reporting period is the reprocessing of the entire moored records of salinity data in the MOVE moorings (from 2000 to present). Earlier publications (Frajka-Williams et al., 2018; Danabasoglu et al., 2021) have discussed disagreements between MOC time series from MOVE and observations from the RAPID-MOCHA-WBTS array at 26°N (Frajka-Williams et al., 2021). At least parts of the disagreements may have been caused by small yet systematic drift behavior in the deep moored salinity data, despite the elaborate CTD cast calibrations that the MOVE project has been doing. This motivated a reprocessing of salinity with an additional calibration step, whereby long-term drifts are deduced from temperature-salinity relationships observed by ships, and corrected in the mooring data. These adjustments are small compared to the nominal sensor accuracies, but large enough to matter for the derived MOC data. Initial results were presented at the April 2022 AMOC meeting and suggest that the reprocessed MOVE time series is in better agreement with the 26°N data. It is still unclear whether MOC signals that are coherent across latitudes, and thereby indicative of a whole-basin signal rather than local circulation, are observable. With the updated MOVE time series, this seems to be the case, and this would be a significant scientific advance if confirmed. Figure 2 shows the updated MOVE time series, including decadal trends, and the 26°N data superimposed. The signs and approximate magnitudes of the decadal trends at both latitudes are consistent and show up- and downturns of about 3 Sv on decadal time scales. Figure 3 shows the locations of the MOVE and 26°N arrays, among others.

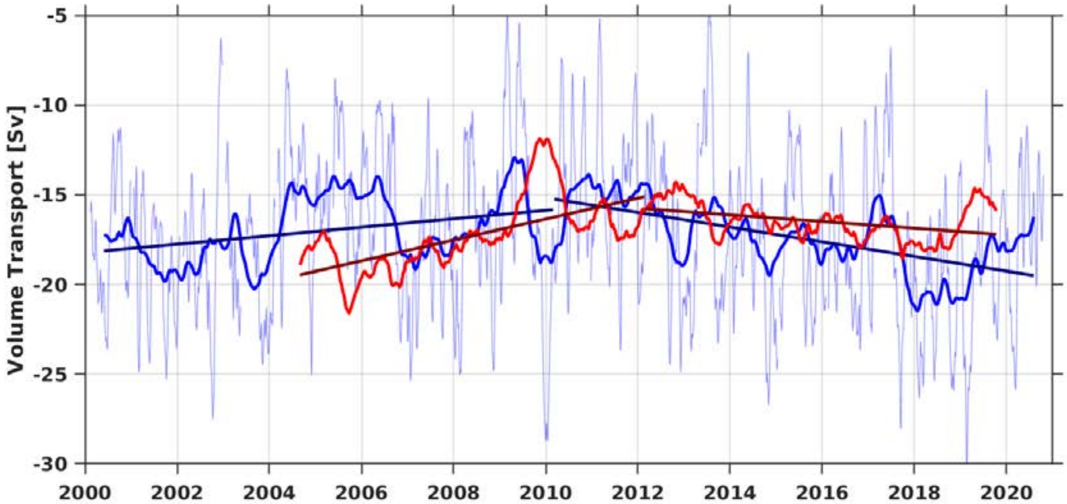

Figure 2: MOC time series from MOVE at 16°N (blue) and the 26°N array (red, Frajka-Williams et al., 2021). The property shown is the ocean volume transport in units of Sverdrup. The sign convention is such that negative signs denote southward flow. Thicker lines show low-pass-filtered data, and the straight lines show linear trends of the corresponding time series. Note that the directions and strengths of the trends roughly agree between 16°N and 26°N.

The MOVE MOC time series is computed from underlying observations of subsurface seawater temperature, salinity, and currents at select locations. These properties are essential ocean variables as per the Global Ocean Observing System (GOOS), as well as essential climate variables as per the Global Climate Observing System (GCOS). MOVE continues to make the direct observations of these essential variables publicly available through the OceanSITES data portals. MOVE does not have routine, real-time data delivery from the subsurface installations, although data can be remotely retrieved when a ship is on station. Instead, datasets are made available in delayed mode. Therefore, the data are for advancing climate, ocean, and related research, rather than routine product delivery or forecasts. On a more informal basis, MOVE maintains a website that contains overview information at: http://mooring.ucsd.edu/move.

3. Outreach and Education

MOVE has no dedicated outreach program, but continues to operate a project website at http://mooring.ucsd.edu/move. The intended target audience consists of unaffiliated scientists and students of oceanography, but it is presented in a form that is understandable to the interested layperson as well. Apart from the website, the following publications and presentations constitute the MOVE outreach and educational efforts:

The publication by Volkov et al. (2021) is part of an annual assessment report about the state of the climate (here: for calendar year 2020), which serves as a reference document for both scientists and non-scientists alike. The publisher's website states that, "its foremost function is to document the status and trajectory of many components of the climate system."

The publication by Berx et al. (2021) is a brief description of observing systems in the Atlantic, including MOVE, that serves outreach and education purposes as well. Figure 3 here is taken from this publication and shows the location of the MOVE array among others, and the important circulation branches that the observing systems are trying to cover.

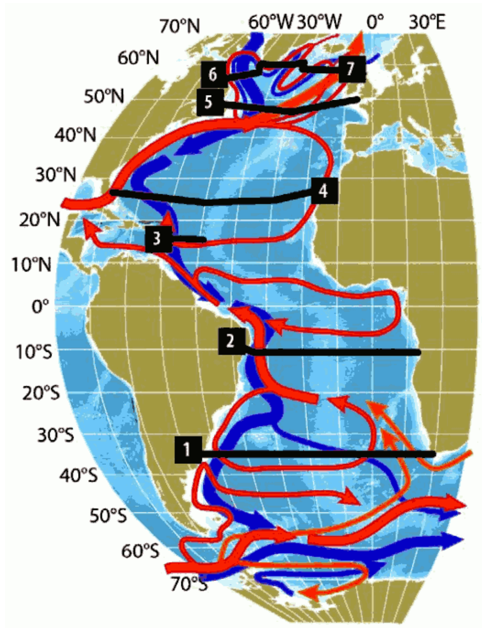

Figure 3: Observing arrays in the Atlantic (numbered), and schematics of major ocean currents (red: surface, blue: subsurface). MOVE is item 3 (see also figure 1), and the 26°N array is item 4. Figure taken from Berx et al. (2021).

4. Publications and Reports

4.1. Publications by Principal Investigators

The following MOVE-related publications are new in the current reporting period:

D. L. Volkov, S. Dong, M. Lankhorst, M. Kersalé, A. Sanchez-Franks, C. Schmid, J. Herrford, R. C. Perez, B. I. Moat, P. Brandt, C. S. Meinen, M. O. Baringer, E. Frajka-Williams, and D. A. Smeed: **Meridional overturning circulation and heat transport in the Atlantic Ocean** [in "State of the Climate in 2020", chapter "Global Oceans"]. *Bulletin of the American Meteorological Society*, 102 (8), S176-S179, 2021.

Barbara Berx, Denis Volkov, Johanna Baehr, Molly O. Baringer, Peter Brandt, Kristin Burmeister, Stuart Cunningham, Marieke Femke de Jong, Laura de Steur, Shenfu Dong, Eleanor Frajka-Williams, Gustavo J. Goni, N. Penny Holliday, Rebecca Hummels, Randi Ingvaldsen,

Kerstin Jochumsen, William Johns, Steingrimur Jónsson, Johannes Karstensen, Dagmar Kieke, Richard Krishfield, Matthias Lankhorst, Karin Margetha H. Larsen, Isabela Le Bras, Craig M. Lee, Feili Li, Susan Lozier, Andreas Macrander, Gerard McCarthy, Christian Mertens, Ben Moat, Martin Moritz, Renellys Perez, Igor Polyakov, Andrey Proshutinsky, Berit Rabe, Monika Rhein, Claudia Schmid, Øystein Skagseth, David A. Smeed, Mary-Louise Timmermans, Wilken-Jon von Appen, Bill Williams, Rebecca Woodgate, and Igor Yashayaev: **Climate-Relevant Ocean Transport Measurements in the Atlantic and Arctic Oceans**. Pp. 10-11 in *Frontiers in Ocean Observing: Documenting Ecosystems, Understanding Environmental Changes, Forecasting Hazards*. E.S. Kappel, S.K. Juniper, S. Seeyave, E. Smith, and M. Visbeck (eds.). A Supplement to *Oceanography* 34(4), 2021. doi:10.5670/oceanog.2021.supplement.02-04.

The following publications are not new, but included for bibliographic reference:

Gokhan Danabasoglu, Frederic S. Castruccio, R. Justin Small, Robert Tomas, Eleanor Frajka-Williams, and Matthias Lankhorst: **Revisiting AMOC transport estimates from observations and models**. *Geophysical Research Letters*, 48, e2021GL093045, 2021. doi:10.1029/2021GL093045.

Eleanor Frajka-Williams, Matthias Lankhorst, Jannes Koelling, and Uwe Send: **Coherent Circulation Changes in the Deep North Atlantic From 16°N and 26°N Transport Arrays**. *J. Geophys. Res. Oceans*, 2018. doi:10.1029/2018JC013949.

4.2. Other Relevant Publications

The following recent publications use or discuss earlier MOVE results:

Tuchen, F.P., Brandt, P., Lübbecke, J.F. and Hummels, R., 2022. **Transports and pathways of the tropical AMOC return flow from Argo data and shipboard velocity measurements**. *Journal of Geophysical Research: Oceans*, *127*(2), p.e2021JC018115.

Biastoch, A., Schwarzkopf, F.U., Getzlaff, K., Rühs, S., Martin, T., Scheinert, M., Schulzki, T., Handmann, P., Hummels, R. and Böning, C.W., 2021. **Regional imprints of changes in the Atlantic Meridional Overturning Circulation in the eddy-rich ocean model VIKING20X**. *Ocean Science*, *17*(5), pp.1177-1211.

Worthington, E.L., Moat, B.I., Smeed, D.A., Mecking, J.V., Marsh, R. and McCarthy, G.D., 2021. **A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline**. *Ocean Science*, *17*(1), pp.285-299.

Wang, H., Zhao, J., Li, F. and Lin, X., 2021. **Seasonal and interannual variability of the Meridional Overturning Circulation in the subpolar North Atlantic diagnosed from a high resolution reanalysis data set**. *Journal of Geophysical Research: Oceans*, *126*(6), p.e2020JC017130.

The following is unrelated to MOVE, but included for bibliographic reference:

Frajka-Williams E.; Moat B.I.; Smeed D.A.; Rayner D.; Johns W.E.; Baringer M.O.; Volkov, D.; Collins, J. (2021). **Atlantic meridional overturning circulation observed by the RAPID-MOCHA-WBTS (RAPID-Meridional Overturning Circulation and Heatflux Array-Western Boundary Time Series) array at 26N from 2004 to 2020 (v2020.1)**, British Oceanographic Data Centre - Natural Environment Research Council, UK. doi:10.5285/cc1e34b3-3385-662b-e053-6c86abc03444

5. Data and Publication Sharing

MOVE is operating according to its data management plan; there have not been any recent changes to this plan. Observational data from moorings and PIES are published via the OceanSITES data centers. Ancillary observational data (CTD casts and water samples) are published through NOAA NCEI. At present, no real-time data are being collected, and all observational data are "delayed-mode". Publications are available on the internet pages of the publishing journals.

6. Project Highlight Slides

(Will be provided separately.)