CLIVAR Report

Climate and Ocean — Variability, Predictability and Change

Workshop Report

Meeting AMOC Observation Needs in a Changing Climate

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1. INTRODUCTION

> *2023 workshop on "Meeting AMOC Observation needs in a Changing Climate"*
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> **What:** A total of 85 participants (as 65 in-person, 20 online and with 40% overall early career participants), from 16 countries met to review the value of AMOC observing, observational priorities and to discuss future AMOC observing.
>
> **When:** 18 - 20 July 2023
>
> **Where:** Hamburg, Germany

The Atlantic Meridional Overturning Circulation (AMOC) plays an important role in modulating air-sea interactions and redistributing heat, freshwater, and biological and chemical properties throughout the Atlantic basin. The need to monitor this redistribution has led to the deployment of numerous intensive observing networks, most notably the AMOC arrays providing continuous transport estimates at different latitudes including 34.5°S (SAMBA; South Atlantic MOC Basin-wide Array), 16°N (MOVE; Meridional Overturning Variability Experiment), 26°N (RAPID), and ~55°N (OSNAP; Overturning in the Subpolar North Atlantic Program). Continuous long-term monitoring at the arrays has provided rich insights into overturning variability, valuable constraints for model assessment and forecast initialization, and raised new questions regarding fundamental aspects of AMOC dynamics.

Despite this legacy, maintaining funding for the AMOC observing networks is challenging and complicated by the requirement for ocean observations to serve increasingly diverse end-user groups. Additionally, since the installation of the RAPID array in 2004, a number of technological advances in ocean observing have been realized: (a) the Argo float profiling array has been at full-strength since ~2007, (b) underwater gliders have become more widely used, (c) gravimetry measured from space is now available, and (d) high resolution altimetry from the SWOT satellite is now available. The success of the observing arrays, the new knowledge gained from observational and modeling efforts, and the new technological advances and the challenges faced by maintaining ocean observing underscore the need for collaboration and coordination across the interdisciplinary oceanographic community.

Workshop. A workshop was held in July 2023 in Hamburg, Germany, following on from 11 previous AMOC Meetings / Workshops held in various places in the US and UK, including the 2019 AMOC Metrics: Coordinating Observations and Modeling Workshop. The primary goal of this workshop was to inform the design of a future-focused AMOC observing system that can provide continuous measurements of key variables while also remaining sustainable over multiple decades. The workshop was organised over 3 days, with additional webinars (7 talks) in the months prior to the workshop. Roughly half of the in-person time was devoted to talks organised over three sessions (i) quantifying the value of AMOC observing, (ii) observational priorities and (iii) roadmap for future observing, with the remaining time for breakout groups and discussions. The meeting was held in hybrid format, with online access including an online discussion group to foster participation by remote participants.

Figure 1. Photo of meeting participants. Photo:Thomas Wasilewski.

Talk sessions. The workshop started with talks on the value of AMOC observing, observational priorities and considering future AMOC observing approaches across three sessions.

Session 1 - Value of AMOC observing: Talks during the workshop and webinars prior to the workshop highlighted the value of AMOC observing. The webinars (https://www.clivar.org/amoc-webinar-series) included latest updates on the observing arrays at 11°S (Rebecca Hummels), Freshwater and the AMOC in the subpolar gyre (Fiamma Straneo), new AMOC transport estimates at 47°N (Monika Rhein), and latest transport estimates from the SAMOC in the South Atlantic (Renellys Perez). Observational records were recognised for providing direct evidence for AMOC variability on a variety of timescales, and processes underpinning variability of AMOC transports (heat, freshwater, carbon, etc.). In addition, they provide a baseline dataset which can be assimilated or leveraged for offline evaluation of models. Comparison between models and observations highlighted discrepancies in the mean AMOC structure, the relationship between the AMOC volume and heat transport, and in processes responsible for AMOC fluctuations. Additional investigations showed that variability in the AMOC is a useful precursor to sea surface temperature (SST) or ocean heat content (OHC) changes in the Atlantic, and has been related to shifts in North Atlantic ecosystems.

Session 2 - Observational priorities: Talks and the differences between talks highlighted the need to systematically collate, discuss and share the quantities of interest (QoI) that should be targeted by AMOC observing efforts. Initial AMOC observing efforts since 2001 focused on the variability of the physical transports (volume, heat and freshwater). More recently the "Atlantic BiogeoChemical (ABC) Fluxes" and "Gases in the Overturning and Horizontal Circulation of the Subpolar North Atlantic (GOHSNAP)" projects have expanded to include measurements of biogeochemical parameters (particularly, dissolved oxygen) across the RAPID and OSNAP arrays (webinars by Elaine McDonagh and Jaime Palter). Initial results have demonstrated methods to estimate both carbon and nutrient fluxes of the AMOC and horizontal gyre circulations, and have the ambition to deepen understanding of changes in the Atlantic carbon sink and biological productivity. In addition, AMOC observing efforts have not yet been explicitly targeted towards the needs of society (e.g., weather and climate forecasting, living marine resource management). As workshop attendees were primarily physical oceanographers and climate scientists, community participation and discussion will need to be expanded in order to address broader scientific and societal needs. Developing explicit targets will provide a basis for more meaningful assessments of a (fit-for-purpose) future AMOC observing system.

Session 3: Knowing what we know now about AMOC processing and observing technology, it was then asked how we should observe the AMOC into the future? The current AMOC observing system–comprising arrays roughly distributed at individual lines of latitude–has yielded a wealth of understanding. But the proliferation of discrete AMOC observing arrays has also highlighted some of the current limitations in the observing system–including different treatments of the geostrophic reference level, and differing requirements for instrument accuracy depending on the observing method employed. In considering a future observing system, the community will need to balance the advantages of maintaining a stable, consistent approach (which allows for trend and anomaly detection) against the benefit of new approaches (e.g., leveraging new technologies and enabling cost-saving solutions through partial array reduction). A range of approaches for evaluating an AMOC observing system were discussed, but without a clear resolution. These included:

- Subsampling existing observations to evaluate degradation in transport estimates;
- Testing distributed methods (e.g., Argo or remote sensing) against existing arrays;
- Running Observing System Experiments (OSEs) where a realistic, high-resolution "nature run" is subsampled according to proposed measurement strategies to evaluate whether these can recover the QoIs simulated in the nature run.
- Running Observing System Simulation Experiments (OSSEs) which assimilate synthetic observations from the nature run into an independent modelling framework to evaluate resulting improvements (i.e., by quantifying the reduction in error relative to the nature run). This approach reveals observation impact on the entire simulated state (i.e., including QoIs remote from the arrays), enabling a more holistic assessment of observation value;
- Using adjoint-based methods to map sensitivities of proposed measurements and target QoIs, reveal dynamical mechanisms underpinning variability in each case, and assess the existence of proxy potential.

This list is not exhaustive, but serves to illustrate varied ways in which observing and modelling efforts have been used to plan and evaluate AMOC observing. It is unlikely that a single approach will provide a robust solution to future AMOC observing and that would be trusted by the community to a sufficient degree to support array reduction. The large uncertainty and spread between models in representing complex transformation processes at high latitudes means that no single model can be used in isolation to plan future AMOC observing. While it is not clear that using multiple models will converge on the "right" answer, the use of multiple models will help guard against shortcomings unique to an individual model. Similarly, a range of tools (e.g., OSEs, OSSEs and adjoints) provide complementary approaches to observing system design. A standardized validation of these frameworks would bolster confidence in their suitability for AMOC observing design applications, and additionally such a framework would reduce the barrier to entry of new groups. An example of a standardized framework is the AMOC METRIC project which provides tools to assess observing arrays across multiple models (e.g., webinar by Gokhan Danabasoglu); by building a tool which is model-grid agnostic (i.e., can be used on different ocean model grids) promotes objectivity in model intercomparisons. How to define a performance threshold (for whether a simulated observing strategy is effective) is still an open question and would require further discussion within the community.

Finally, without extensive collaboration between observational and modeling communities, progress will be limited and slow. This includes exchanging existing data, information on proposed acquisitions, and insights regarding the practicalities of observing system implementation. Examples of the latter include flexibility for changing different components of the observing system and the relative expense of each of these components if cost-saving solutions are sought.

Breakout group (BG) discussions. Following the oral and poster sessions at the workshop, breakout group discussions were organized in small groups of 7-8 participants spanning career stages and including both observing and modeling folks. The discussion topics were (1) "the capabilities, limitations, and priorities of AMOC observing" and (2) "outlining a roadmap for a future AMOC observing strategy", in successive sessions. To initiate structured discussions, BGs were provided with discussion prompts and were asked to focus on a subset of these questions to start with. Following the breakout sessions, summaries were reported back to the whole group. On the final day, the list of recommendations and ideas was distilled into categories (using AI tools to merge similar points) and this list of recommendations was then ranked by workshop participants using the Slido tool. While not rigorous, this process allowed more inclusive participation than would have been possible through simple verbal discussion.

2. SUMMARY AND MAIN RECOMMENDATIONS

Following the initial talks, the breakout groups and discussions, the main recommendations identified by the community of participants were as follows.

- On **observational methods**, the identified needs were: to improve knowledge sharing between observational teams including practical know-how, data product and metadata, and analysis methods (software); to evaluate on a case-by-case basis and, where beneficial, leverage new autonomous, sensor and remote sensing technologies for AMOC-related information (e.g., Argo, SWOT, Smart Cables, and adaptive sampling instruments that can provide sub-surface data to users in real-time); and to support the use of AMOC arrays to measure biogeochemical transports.

- On **modeling methods**, the needs were: to focus on identifying and reconciling key processes missing or poorly represented in numerical ocean and climate models (IPCC AR6); to leverage model output to understand the basin-scale AMOC structure and coherence; to foster focused discussion between observational and modeling groups to design future AMOC observing approaches both at an array-scale and at a basin-scale in order to reduce known uncertainties and standardize strategies to synthesize disparate data sources; and to foster cooperation between modeling groups to build standardized frameworks for observing system assessment and design (e.g., as 'nature runs' in OSEs/OSSEs). The latter includes developing high-resolution, data-constrained state estimates that ingest BGC parameters and ocean velocity data.
- On **impacts and unknowns**, the needs were: to dedicate effort to quantify wider impacts of AMOC variability, e.g., on ecosystems, carbon uptake, terrestrial rainfall and heatwaves, and to identify thresholds in the AMOC system; and to quantify and publish uncertainty of AMOC measurements on various timescales (e.g., monthly to annual).
- On **data management**, the leading-order need identified was: to standardize AMOC data and data product formats, including uncertainties, and to make both data and methods open-access. As a first step, an agreed coordinate system or systems (depth, density, neutral density) should be identified and defined. Particularly for the case of data management needs of the AMOC observing community, it was recognised that these objectives will require significant time-investment to realize, and that the time-investment does not necessarily yield commensurate benefits to early career researchers.
- On **communication**, the need to improve how we link AMOC research to societal needs was raised, including the possibility of developing easier-to-understand indicators for AMOC monitoring and assessment that could be communicated to a wider variety of stakeholders.

These recommendations are in addition to the overall conclusion that continuing to improve our understanding of the AMOC, its variability and evolution, key processes and predictions is a fundamental aim of the AMOC community. The current AMOC observing system has underpinned significant advances in our understanding of the AMOC and its complexity, and the capability to develop process-level understanding must be a priority for a future observing approach. This conclusion is also evident from the latest IPCC AR6 report, in which WGI identified that the scientific community's reduced confidence in AMOC's past and future behavior (relative to the SROCC and AR5) stems in part from discrepancies between observing and modeling efforts, and missing key processes in models used to construct projections. The AMOC community is quite vibrant as also evidenced by the interest and meaningful engagement of the workshop participants (including a high proportion of early career researchers, ~40%). The final question asked of workshop participants was what the CLIVAR AMOC Task Team should do to support the AMOC community, which identified three nearterm foci: (i) to facilitate data and data product availability from AMOC observing arrays, (ii) to coordinate an AMOC summer school, and (iii) to coordinate a workshop on AMOC modeling.

This CLIVAR workshop stimulated a robust exchange of ideas within the community of AMOC scientists. Webinars leading up to the workshop laid out existing AMOC knowledge across a range of approaches to provide background information, while science talks during the workshop identified current needs and ideas for future observing strategies. Ample time was allocated for breakout groups and discussions, with workshop methods chosen to foster participation across career stages and backgrounds, and technical tools used to aid in synthesizing findings during a condensed (3-day) meeting into the set of actionable priorities described above. Many of these items cannot be carried out in isolation, or at least not as effectively, particularly when considering how to design a robust observing system. Instead, coordinated approaches will provide the required confidence in a recommendation for a future AMOC observing system.

3. ACKNOWLEDGEMENTS

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APPENDIX A: ACRONYMS

ABC	Atlantic BiogeoChemical Fluxes
AMOC	Atlantic Meridional Overturning Circulation
ARGO	Array for Real-Time Geostrophic Oceanography
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
BGC	Biogeochemical
CLIVAR	Climate and Ocean: Variability, Predictability and Change
EPOC	Explaining and Predicting the Ocean Conveyor
GOHSNAP	Gases in the Overturning and Horizontal Circulation of the Subpolar North Atlantic Program
IPCC	Intergovernmental Panel on Climate Change
MOVE	Meridional Overturning Variability Experiment
OHC	Ocean Heat Content
QoI	Quantities of interest
OSEs	Observing System Experiments
OSSEs	Observing System Simulation Experiments
OSNAP	Overturning in the Subpolar North Atlantic Program
RAPID	Rapid Climate Change programme
SAMBA	South Atlantic MOC Basin-wide Array
SROCC	Special Report on the Ocean and Cryosphere
SST	Sea Surface Temperature
SWOT	Surface Water Ocean Topography
WGI	Working Group I
WMO	World Meteorological Organization
WCRP	World Climate Research Programme

APPENDIX B: ORGANISERS

The scientific organisers were Eleanor Frajka-Williams (Universität Hamburg, Germany), Peter Brown (National Oceanography Center, UK), Eric Chassignet (Florida State University, USA), Gokhan Danabasoglu (National Center for Atmospheric Research (NCAR), USA), Nick Foukal (Woods Hole Oceanographic Institution (WHOI), USA) and Helen Pillar (The University of Texas at Austin, USA), with support from Kaja Scheliga (Universität Hamburg) and Jing Li (WCRP CLIVAR).

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APPENDIX D: AGENDA

Book of Abstracts

Agenda: Schedule-v1-AMOCworkshop.pdf