Highlights from 2014 US AMOC Science Team Meeting

The US AMOC Science Team, now in its seventh year, convened its bi-annual meeting this year in Seattle, Washington, September 9-11. A total of 82 participants, including investigators from funded US AMOC projects, additional interested scientists and students within and outside the US, and agency program managers, met to share recent research results, identify gaps in our understanding and measurement of AMOC, coordinate efforts and start new collaborations among the Science Team members, and discuss the program's emerging near-term priorities as well as its long-term goals. The meeting was organized in Task Team focused sessions addressing each of the four program objectives: implementation and evaluation of the AMOC observing system; an assessment of AMOC state variability and change; an assessment of AMOC variability mechanisms and predictability; and an assessment of the role of AMOC in global climate and ecosystems. A special session highlighted research and focused discussion on AMOC linkages with climate variability and change. Highlights from each of the sessions are provided below. A full report on 2014 progress of the Science Team will be issued in early 2015.

Task Team 1: AMOC Observing System Implementation and Evaluation

The discussions for Task Team 1 (TT1) made it clear that the existing near-term priorities continue to be high priorities for AMOC studies, particularly maintaining and extending the existing AMOC time series (RAPID/MOCHA/WBTS and MOVE) as well as fully implementing the newer OSNAP and SAMBA/SAMOC systems. Many new and continuing high latitude North Atlantic projects illustrating the links to the Arctic were also presented and were viewed quite positively.

Regarding new priorities, one area that came out as a clear new near-term priority is to improve both the availability and the usability of the AMOC estimates presently being made. Specific action items here included: 1) ensuring that AMOC estimates (and the key underlying measurements collected as part of the AMOC estimates) are being made available in widely recognized locations such as the World Ocean Database, OceanSITES, NODC, BODC, etc.; and 2) ensuring that alongside AMOC estimates (and the constituent components) are error estimates that are applicable at time scales of days, weeks, months, and years to provide necessary precision information for numerical models (when data is used for validation and/or when data is assimilated) and for inter-array comparisons.

A second new near-term priority that was discussed was improving communication across the observing systems groups, both between existing observing programs in the North and South Atlantic, and between more established observing system groups and newer groups becoming involved at the national and international levels. Specific action items included setting up small working groups to address specific issues (e.g. understanding the opposite AMOC trends observed by the MOVE and RAPID/MOCHA/WBTS arrays), involving researchers from all AMOC arrays (high latitude North, subtropical North, and South Atlantic) when planning workshops and conference special sessions, and involving international partners who have not generally been involved in our USAMOC meetings (e.g. the German science group doing the new AMOC array at 11°S).

Regarding the long-term priorities for TT1, the discussion focused around finding new technologies and/or methods that can be used to maintain the long time series, since making these measurements for 20+ years is likely needed to provide the temporal coverage required for proper analysis, but financial realities may make existing systems too expensive for long-term maintenance. Oral and poster presentations covered some potential future technologies that could reduce ship time requirements (e.g. Deep Argo, gliders, EM observations, data pod technology), but it was clear that additional work and consideration in this area are needed.

Finally, while not leading specifically to new ideas for near-term or long-term priorities, the group discussed the importance of evaluating interior pathways in the basin such as those found by RAFOS process studies in the high latitude North Atlantic. There was a suggestion that these pathways would likely be observed primarily via Lagrangian methods in the near-term due to limited funds for new fixed-site observing systems. The group also discussed the need for more rigorous testing of data assimilation schemes that are using the data collected by TT1 projects – specifically via the use of an independent 'perfect' model that would be subsampled and then assimilated into a family of unrelated models in order to test and improve our understanding of these assimilation systems and their results. It was also noted that only a handful of researchers from the assimilation community were present at the meeting, and that we should reach out more to the assimilation community.

Summary of Action Items:

1. Ensure that AMOC estimates, and the key underlying measurements collected as part of the AMOC estimates, are being made available in widely recognized locations (e.g., national and international data centers).
2. Ensure that alongside AMOC estimates (and the constituent components) that are made publicly available, error estimates that are applicable at time scales of days, weeks, months, and years are also provided.
3. Encourage small working groups to address specific issues (e.g., understanding the opposite AMOC trends observed by the MOVE and RAPID/MOCHA/WBTS arrays).
4. Encourage involving researchers from all AMOC arrays (e.g., 55°N, 26°N, 16°N, 11°S, 34.5°S) when planning workshops and special sessions during national and international conferences.
5. Seek the involvement of international partners who have not generally been involved in USAMOC meetings (e.g., the German science group doing the new AMOC array at 11°S).
6. Seek new technologies and/or methods that can be used to sustain the AMOC observational programs and reduce the costs.
7. Encourage rigorous testing of data assimilation schemes via the use of an independent 'perfect' model that would be subsampled and then assimilated into a family of unrelated models in order to test and improve our understanding of these assimilation systems and their results.
8. Encourage/seek the participation of additional researchers from the assimilation community in future USAMOC meetings.

Task Team 2: AMOC State, Variability and Change

The discussion of Task Team 2 (TT2) focused on integration of modeling and observational efforts to characterize AMOC and other descriptors of Atlantic climate variability and change over the last several decades and into the future. AMOC is an emergent, integrated, property of the ocean and thus provides a useful comparison for data assimilation models that primarily assimilate basin wide data such as sea level, temperature and salinity. Point measurements such as moored observations that are used to estimate AMOC in the RAPID/MOCHA program at 26°N can serve as useful tests of the state estimates as well as forward models. A comparison of state estimation products of AMOC at 26°N shows large disagreement with its temporal evolution while hind-cast models sometimes perform better. The importance of providing uncertainty bounds on both the observational estimates as well as the error estimates from assimilation products was emphasized.

Over the next several years, TT2 needs to focus on quantifying connections between the subtropics and the subpolar regions, coordinating analyses with OSNAP observational efforts. Another priority is to continue to work on developing relationships between AMOC and other quantities that are more easily observed, thus create "fingerprints" or "metrics" of AMOC variability. These quantities could include upper ocean heat content, estimates of circulation and transport pathways. A focus on variables that are more directly related to impacts, predictability and mechanisms is important as we move into the future. Long-term priorities include understanding of linkages between South Atlantic Ocean and Southern Ocean, and the North Atlantic and Arctic and the Atlantic Ocean and the rest of the climate system. In addition, over the next decade, the community needs to determine what sustained observations can help us to achieve the goal of decadal predictability from AMOC related processes.

Summary of Action Items:
Coordination with the data assimilation/state estimation community, including

1. Encourage observational community provide error estimates for derived/integrated quantities such as AMOC and MHT.
2. Encourage state estimation community to make the incremental adjustments that occur during the data assimilation process available to the community.
3. Development of metrics for Atlantic climate variability from a variety of perspectives.

Task Team 3: AMOC Mechanisms and Predictability

Task Team 3 (TT3) priorities and activities were the focus of two sessions of the 2014 US AMOC Science Team meeting: a half hour plenary discussion and an hour and half breakout discussion. Neither of the sessions elicited any specific recommendations for changes to TT3 near-term priorities or long-term goals, which appear adequate as currently articulated. In plenary, there was vigorous discussion about the relative merits of high resolution and idealized modeling in TT3 research. While it was generally agreed that more eddy-resolving modeling should be encouraged, in particular for process studies which could help in the critical evaluation of AMOC mechanisms identified in lower resolution or idealized models, there was considerable opposition to the idea of moving towards order (0.25^{o}) ocean models as a "workhorse" tool for AMOC research. Opponents argue that such grids represent a "no man's land" of resolution for which it is unclear whether or how to implement conventional mesoscale eddy parameterizations, and that the extra expense is not justified by any significant change in simulation fidelity.

The TT3 breakout continued the discussion of how high-resolution modeling can be brought to bear on questions of AMOC mechanisms. Some areas of focused future effort suggested include: exploration of the sensitivity to coupling frequency, particularly as horizontal resolution is increased; coordinated high-resolution intercomparison experiments similar to the efforts under the Coordinated Ocean-ice Reference Experiments (CORE) umbrella, such as a tracer release or interannual variability protocol for eddy-resolving models; a greater focus on diabatic processes (both at the surface and in the abyssal ocean) and how they change with model resolution. It was noted, however, that even order (0.1^{o}) eddy-resolving models are unable to explicitly resolve important Nordic Sea overflow physics. Another line of research to be encouraged is the use of high-resolution models to shed light on persistent model bias (for example, in the North Atlantic and Southern Ocean) because these biases call into question the conclusions about AMOC variability and mechanisms drawn from workhorse climate models.

Summary of Action Items:

1. Develop a collaborative review article summarizing current state-of-knowledge regarding AMOC variability mechanisms as well as important outstanding gaps in our understanding.

Task Team 4: Climate Sensitivity to AMOC: Climate/Ecosystem Impacts

Task Team 4 focuses on how a changing AMOC affects other parts of the climate system through the sensitivity and response of these to perturbations in the content and distributions of ocean heat, fresh water and carbon. Discussions during the meeting and breakout session identified four principal themes constituting a framework for this group's near-term priorities.

The first theme was the i*mpacts of AMOC variability on global mean temperature.* The topics of highest priority within this theme include the causes of change in the rate of warming (e.g., the recent observed hiatus in the upper ocean), consequences for tropical cyclone activity (e.g., via upper ocean heat content and vertical shear), and associated shifts in the Inter-Tropical Convergence Zone and tropical precipitation patterns.

The second theme was the i*mpacts of AMOC variability on the cryosphere,* particularly Arctic sea ice and the Greenland Ice Sheet. During the discussions, it was noted that the Greenland Ice Sheet WG has produced a very well-organized framework for pushing research forward, including a focus on ice sheet-ocean interactions and expanding the ocean-ice observing system. This led to specific questions regarding Arctic sea ice as it relates to AMOC, including:

- How will changes in the AMOC influence Arctic sea ice regionally and as a whole?
- What mechanisms are seasonally important (winter versus summer)?
- What is the fate of heat transport through Fram Strait and in the Barents Sea? And what are the processes that control this in models?

The third theme focused on the *impacts of AMOC variability on global/regional sea level rise.* Within this theme, the discussion identified a couple of research areas of interest such as the influence of AMOC on the dominant processes controlling observed variability in the rates of regional sea level rise (i.e., thermosteric and mass input) and understanding why regional sea level along the US east coast is greater than the global average and the linkage with AMOC.

The fourth theme was the *impacts of AMOC variability on ocean-atmosphere exchanges of carbon, biogeochemical cycles, and associated changes in marine ecosystems.* The group identified some of the near-term priority questions, including:

- How can the paleo record be utilized to better understand the impact of AMOC on ocean carbon uptake and the terrestrial carbon cycle?
- What processes are controlling carbon draw down into the deep ocean and variability in that system?
- What physical parameters (i.e., upper ocean stratification, mixed layer depth, nutrient input) are needed by the ocean carbon/biogeochemistry community to improve understanding of these?
- Does satellite productivity correlate with AMOC variability?

Summary of Action Items:

1. Connect with existing US CLIVAR working groups (i.e., Hurricane WG, Extremes WG) to assess the degree to which AMOC variability is causally linked to observed and projected shifts in these climate phenomena.
2. Promote studies within the Arctic observational and modeling communities investigating how AMOC variability will affect Arctic sea ice in the near future.
3. Coordinate with the Coastal Ocean Observing community (e.g., MARACOOS) to assess the linkages between AMOC and the changes observed on the shelves.
4. Connect with the Ocean Carbon Biogeochemistry program to proactively assess the high priorities of the carbon and biogeochemical research communities. Where can the AMOC community contribute with respect to better understanding carbon uptake, changes in temperature, upwelling, and other physical processes influencing ecosystems dynamics and geographic distributions?
5. Attend the Southern Ocean and Ocean Carbon Uptake joint workshop in December 2014 at AGU Fall Meeting.