CONNECTING PALEO & MODERN OCEANOGRAPHIC DATA TO UNDERSTAND ATLANTIC MERIDIONAL OVERTURNING CIRCULATION OVER DECADES TO CENTURIES

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CONTRIBUTORS

Hali Kilbourne (U. Maryland), Marlene Klockmann (Max-Planck-Institute for Meteorology), Eduardo Moreno-Chamarro (Max-Planck-Institute for Meteorology), Pablo Ortega (U. Reading), Anastasia Romanou (NASA GISS), Meric Srokosz (National Oceaongraphy Centre), Zoltan Szuts (U. Washington), Kaustubh Thirumalai (U. Texas-Austin), Ian Hall (Cardiff U.), Patrick Heimbach (U. Texas-Austin), Delia Oppo (Woods Hole Oceanographic Institution), Andreas Schmittner (Oregon State U.), Rong Zhang (NOAA GFDL)

EDITOR

Kristan Uhlenbrock, US CLIVAR Project Office

FRONT COVER IMAGE

A composite of the thermohaline circulation and laminated sediment core. Credit: (globe) NASA/Goddard Space Flight Center Scientific Visualization Studio The Blue Marble Next Generation data is courtesy of Reto Stockli (NASA/GSFC) and NASA's Earth Observatory, and (sediment core) Laurence Dyke and the Petermann 2015 Scientific Party.

BACK COVER IMAGE

A scientist drills coral to collect cores for paleoclimate analyses off the coast of Florida. Credit: Don Hickey, USGS.

Table of Contents

1 INTRODUCTION

Variations in the Atlantic Meridional Overturning Circulation (AMOC) have implications for global and regional climate, ocean biogeochemistry, and food webs. The potential for AMOC to have a tipping point that transitions to a stable reduced state triggered by fresh water input (Hand 2016; Rahmstorf 2000) makes it a particularly important phenomenon to understand, in order to predict potential state shifts in response to anthropogenic global warming. Concentrated international efforts have led to great progress improving our understanding of AMOC in the modern ocean using a combination of observational and modeling approaches. At the same time, paleoceanographers have made much progress towards understanding AMOC before the instrumental period. So far there has been limited crossover between these two communities, though there is great potential for synergy in moving the science of AMOC forward, especially with regards to understanding AMOC mechanisms and impacts over timescales of decades to millennia. By way of introduction, we outline some recent advances from the modern and paleo oceanographic communities and highlight some outstanding questions where collaboration and communication across the two disciplines may be particularly fruitful.

Modern AMOC Observations

Although observations of the AMOC have been collected sporadically ¾ for example, five observational studies were conducted at 25˚N between 1957 and 2004 (Bryden et al. 2005) ¾ continuous observations of its strength and vertical structure only exist since the deployment of moorings in 2004 across 26.5˚N by the joint UK RAPID-US Meridional Overturning Circulation and Heatflux Array (MOCHA) project. More recently, in 2014, the international Overturning in the Subpolar North Atlantic Program (OSNAP) deployed moorings and gliders across the subpolar North Atlantic between Canada and Greenland, and Greenland and Scotland, to monitor the AMOC at higher latitudes (Hand 2016). These observations will help in determining the meridional coherence of the AMOC. At the same time, a system to observe the AMOC in the South Atlantic is also being implemented (Ansorge et al. 2014). Summaries of what has been learned from these observations can be found in the reviews of Lozier (2012), Srokosz et al. (2012), and Srokosz and Bryden (2015). Some key results from the observations that have overturned our understanding of the AMOC are summarized briefly:

- The AMOC has strong variability on timescales of days to a year.
- The AMOC has been declining over the 2004-2014 decade.
- The AMOC may not be meridionally coherent on some timescales.
- The deep western boundary current is not the only path of the AMOC out of the subpolar North Atlantic.

In addition, it is important to note that the mechanisms responsible for the variability of the AMOC over different timescales are not well understood. Therefore, while significant progress has been made, unanswered questions remain.

Paleo AMOC Observations

Paleoceanographic studies of AMOC span from the onset of AMOC with the formation of the Atlantic Ocean basin through orbital timescales, millennial-scale variability, and centennial to decadal scale variability of AMOC from the Holocene into historical times. The evidence for past AMOC variability comes from a variety of paleoclimate proxies, including marine sediment cores and other natural archives such as ice cores, corals, bivalves, and speleothems. Deep ocean circulation is of particular interest to paleoclimatologists because the ocean has most of the mass, thermal inertia, and carbon of the ocean-atmosphere system (Adkins 2013). Much of the effort and successes of recent years have focused on the abrupt climate changes observed during the last glacial-interglacial cycle and the potential for them to be caused by or cause rapid changes in AMOC strength (e.g., Alley 2007; McManus et al. 2004; Rahmstorf 2002; Timmermann et al. 2010). AMOC has become the hypothesized link between observations of episodic large freshwater discharges from Northern Hemisphere glaciers, large and rapid temperature fluctuations over the Greenland ice cap, and anti-phased temperature anomalies between the Northern and Southern Hemispheres (Henry et al. 2016). These very large perturbations to the system likely occurred over, at most, a few decades (Rahmstorf 2002), making them very relevant to modern oceanographers.

The possibility that similar dynamics could be important for smaller climate perturbations during the Holocene and under future global warming conditions (Denton; Broecker 2008) has led to research on centennial and multidecadal climate variability, especially focused on the North Atlantic over the last millennium.

Paleoclimate research on AMOC variability over this timescale can be broken up into three main thrusts:

1. Identifying the existence, persistence, or character of a multidecadal mode of variability (Atlantic Multidecadal Variability) in the climate system (see the review in Kilbourne et al. (2014));
2. Reconstructing patterns of Atlantic ocean temperatures that are thought to be associated with potential changes in AMOC (e.g., Mann et al. 2009; Rahmstorf et al. 2015; Reynolds et al. 2017; Sicre et al. 2014); and
3. Estimating circulation changes in key areas of the ocean from proxies that are thought to be directly related to water mass transports (e.g., Lund and Curry 2006; Mjell et al. 2015; Moffa-Sanchez et al. 2015).

Results from these types of studies are often contradictory, and much work is needed to generate a consensus view of the evolution of AMOC and its associated climate impacts over the last 1000 years.

Modeling AMOC

Modeling is an important tool for understanding AMOC on all timescales. Mechanistic studies of modern AMOC variability have been hampered by a lack of consistency between free-running models and the sensitivity of AMOC to resolution and parameterization (see Tulloch and Marshall (2012) and references therein). Recent work within the framework of the phase two Coordinated Ocean- Reference Experiments (CORE-II) addresses this issue head on, looking at model differences of AMOC mean state (Danabasoglu et al. 2014) and interannual variability (Danabasoglu et al. 2016). One consistent feature across the models is that AMOC mean transport is related to mixed layer depths and Labrador Sea salt content, whereas interannual variability is primarily associated with Labrador Sea temperature anomalies (Danabasoglu et al. 2016). This is consistent with the hypothesized importance of salt balance for AMOC variability on geological timescales (e.g., Zhang et al. 2015). The simulated relationships between AMOC and subsurface temperature anomalies in fully coupled climate models reveal subsurface AMOC fingerprints that could be used to reconstruct historical AMOC variations at low frequency (Wang and Zhang 2013; Zhang 2007; Zhang 2008).

With the lack of long-term AMOC observations, models of ocean state that assimilate observational data have been explored as a way to reconstruct AMOC, but comparisons between models indicate they are quite variable in their AMOC representations (Karspeck et al. 2015; Munoz et al. 2011; Tett et al. 2014). Karspeck et al. (2015) found that historical reconstructions of AMOC in such models are sensitive to the details of the data assimilation procedure. The ocean data assimilation community continues to address these issues through improved models and methods for estimating and representing error information (Stammer et al. 2016).

Two objectives of paleoclimate modeling are 1) to provide mechanistic information for interpretation of paleoclimate observations, and 2) to test the ability of predictive models to simulate Earth's climate under different background forcing states. In a good example of the first objective, Schmittner and Lund (2015) and Menviel et al. (2014) provided key information about the proxy signals expected under freshwater disturbance of AMOC, which were used to support the paleoclimate observations made by Henry et al. (2016). In an example of the second objective, Muglia and Schmittner (2015) analyzed Third Paleoclimate Modeling Intercomparison Project (PMIP3) models of the Last Glacial Maximum (LGM) and found consistently more intense and deeper AMOC transports relative to preindustrial simulations, counter to the paleoclimate consensus of LGM conditions (Gebbie 2014), indicating that some processes are not well represented in the PMIP3 models. One challenge is to find adequate paleo observations against which to test these models (Harrison et al. 2016). PMIP is now in phase 4 (part of CMIP6), which includes experiments covering five periods in Earth's history: the last millennium, last glacial maximum, last interglacial, and the mid-Pliocene (Kageyama et al. 2016). Newly compiled paleoclimate datasets from the PAGES2k project, more transient simulations, and participation of isotope enabled models planned for CMIP6/PMIP4 will enable richer paleo data-model comparisons in the near future.

Workshop Motivation, Goals, and Structure

In order to further understand the variability of AMOC, we knew that the paleo and modern oceanographic communities needed to cooperate more to identify inadequacies in the instrumental record, where paleo data and modeling could be useful, and how best to merge results from both communities. Driving the initiation of this workshop, we identified these fundamental questions:

1. AMOC has been linked to global climate anomalies (e.g., hemispheric temperature gradients, intertropical convergence zone (ITCZ) position) on geologic timescales; do similar processes drive decadal- to centennial-scale variability in the Earth system?
2. Is it possible to use paleoclimate data and modeling to better our understanding of both forced and unforced AMOC variability, perhaps enabling us to de-convolve anthropogenic forcing from modern observations and better predict future AMOC variations?
3. How do the recent changes observed in AMOC compare with AMOC variability in the past, over recent centuries, and through recent glacial/interglacial cycles? Is the observed decadal-scale slowdown within the range of normal variability, or is it unusual?

The overarching workshop goals were to combine forces of both paleo and modern communities to explore the state of knowledge of AMOC over decades to centuries and to identify promising and potentially synergistic research directions to better understand AMOC and its relationship to climate variability. More specifically, we focused on the following science objectives:

- Explore how we can best bridge the gaps between modern and paleo observations of AMOC to reconstruct the history of AMOC variability over the last few centuries to millennia because it is central to other AMOC-related science questions on which we hope to make progress;
- Discuss ways to test hypotheses about the mechanisms behind AMOC variability on multidecadal to millennial timescales;
- Identify the potential impacts of AMOC variability, investigate what paleo data can tell us about those impacts, and think about how they might be used as fingerprints to explore AMOC variability; and
- Spark new research ideas across the disciplinary divides and promote new collaborations and cooperative research among participants.

To accomplish these objectives, the workshop convened over three days, from May 23–25, 2016, in Boulder, Colorado, at the National Center for Atmospheric Research Center Green Campus. The agenda was organized around three plenary sessions, each with 2-3 invited summary talks and 11-13 poster presentations. Posters were introduced with three-minute "lightning talks." The presentations are available via the workshop website. Significant time was dedicated to breakout groups and discussion to illuminate findings and identify recommended actions to accelerate scientific progress.

We had over 60 participants attend the meeting, including 21 early career scientists and 22 scientists from institutions outside the US – five from developing countries. Attendance was comprised of both modern and paleo observationalists and modern and paleo modelers, with approximately even participation from the modern and paleo communities. To encourage and enable early career scientist and student participation, reduced registration fees and travel support was provided.

2 WORKSHOP SESSIONS

The workshop was organized around three sessions to better understand AMOC state and variability, mechanisms and predictability, and impacts on the climate, ecosystems, and biogeochemistry of the Earth system. The following sections summarize presentations and discussions for each of these sessions.

Session 1: AMOC State and Variability

This session addressed our understanding of the AMOC and its timescales of variability. The two keynote talks outlined perspectives from modern observations and from proxy records over the last millennium.

The modern view is based on observations from the last 15 years, including measurements of AMOC strength from the RAPID array and of other relevant ocean currents from drifter and satellite data. The recent observations challenge the common assumptions of AMOC as being slowly varying, large-scale, continuous in pathways, and coherent in space. These assumptions are mostly based on large-scale theory, sparse hydrographic observations, and numerical models, and do not account for mesoscale eddies, short-term variability, or the dominance of winds for driving AMOC variability. It is still unclear whether available time series are simply too short to confirm mechanisms acting on long timescales or whether the existing assumptions on the AMOC need to be revised. For instance, the strong link between deep-water formation and AMOC strength, as suggested by numerical models and paleo records, is not supported by the recent observations. These observations are suitable for studying seasonal to interannual variability but are not yet long enough to address decadal variability. Putting the observational record into its historical context is, therefore, crucial for addressing the general questions of why and on which timescales the AMOC changes, and if the recent decline is due to decadal variability or a response to climate change.

Paleo AMOC observations may be either indirect reconstructions of variables controlled by AMOC variability or direct ocean circulation proxies, and both types were presented during the workshop. Direct ocean circulation proxies include: foraminiferal $\delta^{18}O$-based thermal wind calculations (an especially difficult but physically meaningful method), isotopic ocean tracers in biogenic carbonates (Nd_{ε}, $^{231}Pa/^{230}Th$, $\delta^{13}C$, $\Delta^{14}C$), and sediment grain size analyses of water flow rates. There is a wide range of indirect reconstructions of AMOC. At one end are so-called fingerprints of AMOC, such as the temperature difference between the anomalously cold region in the subpolar gyre and the rest of the northern Atlantic, or sub-surface temperature anomalies in the western tropical Atlantic. At the other end are associated variables, such as the temperature and salinity structure of the subpolar gyre, coastal sea level changes next to the western boundary current, and the average North Atlantic temperature anomaly.

The existing paleo AMOC data remain too sparse to generate a consistent picture of AMOC variability over the last millennium. It is unclear if inconsistencies between reconstructions are due to reconstruction errors and uncertainties, or if perhaps they are caused by the lack of spatial coherence of ocean circulation itself on these timescales. Further work with proxy validation and generating multiple records from the same regions will provide a way to quantitatively assess signal versus noise in AMOC reconstructions.

Paleo reconstructions of the AMOC components face significant challenges. Major factors for AMOC reconstructions are the inherent timescale of the archives and where they tend to be found. Annually to sub-annually resolved proxies, such as tree-rings, corals, bivalves, and some sediment cores, ice cores, and cave deposits, are usually found in terrestrial or coastal to continental shelf environments. Marine sediment cores that can contain information about open ocean conditions usually have lower temporal resolution, though high-deposition-rate cores can have multidecadal to centennial scale time resolution. Potential sampling sites for such high-resolution cores are very limited and do not necessarily correspond with locations suitable for AMOC studies (Figure 1). Ideally AMOC reconstructions from the high-resolution archives can be used as a bridge to quantifiably link modern observations with

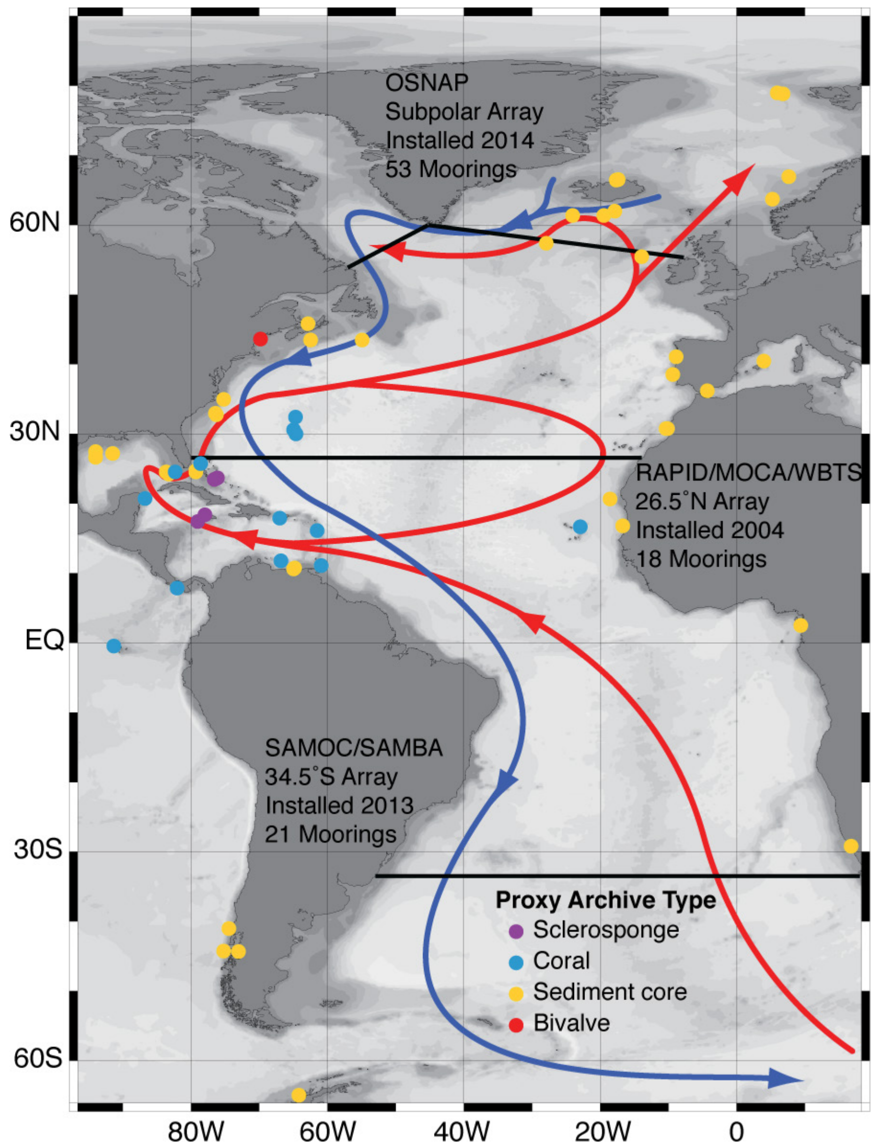

Figure 1: The map shows the locations of some existing paleoceanographic and modern oceanographic AMOC observing systems. Paleoceanographic sites represent the locations of samples/cores with paleo temperature information archived in the PAGES 2k proxy temperature data set version 2.0.0 (PAGES2k-consortium 2017)

lower-resolution, longer records from marine sediment cores. Additionally, modeling work can be particularly helpful to identify AMOC fingerprints and could be used to identify locations and types of future proxy sampling. Models enabled with geochemical tracers commonly measured in paleoclimate proxies, such as carbon and oxygen isotopes, can be particularly useful for both identifying optimal sites to generate paleoclimate reconstructions and also for interpreting signals observed. Continued focus on proxy forward modeling would be helpful to maximize the utility of such information.

A significant barrier to linking modern observations with paleoclimate records is finding a common method for quantifying AMOC. The standard zonally integrated estimate of AMOC transport is difficult to extract from proxy records. Most reconstructions address only spatially limited components of the AMOC, such as Gulf Stream intensity or AMOC fingerprints (i.e., water mass distributions, surface temperature patterns, or sea level change). Modern observations and model simulations of AMOC strength, in addition to showing large differences themselves, are difficult to compare directly to proxy data. Defining common metrics of interest could enable an easier comparison between observations, models, and proxies.

In discussing the intersection of modern and paleo climate studies, we agreed that sustained communication is important for sharing mutually useful knowledge specific to different fields. This includes knowledge about available historical instrumental records and proxy databases or about the advantages and caveats of specific datasets such as ocean/atmosphere reanalyses. Continued communication will also help form a shared vocabulary. For instance, it is common in both fields to test the ability of the observing system to represent the process of interest in an idealized model experiment, but the method is referred to very differently by practitioners: OSSE (observing system simulation experiment) and pseudo-proxy experiment.

A better mechanistic understanding is also crucial for bridging modern and paleo information. Well-constrained models could be used to fill the gap between the modern observations and the proxy data. However, a simulated ocean state-estimate in accordance with observations is already difficult to obtain for the modern ocean and even more difficult for the available proxy data. But if models succeeded in reliably reproducing key centennial mechanisms, those models could also be used to study variability on shorter timescales. Although the general consensus is to emphasize the last millennium, and possibly the late Holocene, paleo studies of older periods (e.g., last glacial cycle, Pliocene) are helpful for the mechanistic understanding. These periods have very large and different forcings and, therefore, provide a better signal-to-noise ratio compared to the last thousand years.

Session 2: AMOC Mechanisms and Predictability

Although there have been recent efforts to describe the mechanisms responsible for AMOC changes from interannual to millennial timescales using multiple lines of evidence — from modern observations (like the RAPID project) and paleo reconstructions to modeling studies — these do not provide, yet, a complete and consistent picture of the relevant processes and drivers. Indeed, the fact that AMOC variability is highly model dependent, hard to measure, and difficult to reconstruct has led to large uncertainties in our current understanding of AMOC variability and predictability.

Paleo reconstructions, like the instrumental record, hold promise for benchmarking model output. Furthermore, to the degree that models are over-tuned to the current climate, there is value in testing their performance using the paleo record.

We discussed several potential mechanisms for AMOC variability on decadal and greater timescales that could be investigated further. Primarily they focus on buoyancy anomalies in the deepwater formation areas. The role of the density structure of the Labrador Sea was considered, as well as the intensity of the Nordic seas over flows and the balance between the overflows and Labrador Sea convection. We generally agreed that investigations into the response of deepwater formation to freshwater inputs, from Arctic sea ice and the Greenland ice sheet, was of interest, especially in light of melt due to anthropogenic warming. Forcing from the atmosphere (e.g., North Atlantic Oscillation) and the advection of buoyancy anomalies from near (subpolar-subtropical gyre boundary) and far (cross-equatorial freshwater transport, Agulhas leakage) were important potential contributors to AMOC variability over a range of timescales. Connections to the Southern Ocean were considered important but difficult to corroborate with paleoclimate data on shorter timescales because marine sediments in the region are characterized by low-sedimentation rates and high-dissolution rates for biogenic carbonate.

One of the main challenges that emerged during the workshop was the identification of optimal ways to compare the different aspects of AMOC variability described by paleo data and models. In discussing the most relevant time periods for such a comparison, the past 200–300 years arose as one key interval — owing, first, to the large availability of proxy data overlapping modern observations and, second, to the possibility of performing climate simulations driven with better constrained radiative forcing estimates. Targeting this period is also essential for deciphering whether the AMOC has weakened over the course of the 20th through 21st centuries in response to recent climate change. In addition, modeling climate and AMOC under different background climate states with new equilibrium and transient climate simulations is a productive way to investigate past AMOC changes and its driving mechanisms at different timescales. Expanding transient experiments particularly will help us move beyond simulations of the mean state to include variability and non-equilibrium processes. These efforts should be directed to capitalize on the previous PMIP3 simulations and complement the envisaged PMIP4 and Sixth Coupled Model Intercomparison Project (CMIP6) experiments (e.g., last millennium, mid-Holocene, last deglaciation, Last Glacial Maximum) by focusing on other relevant periods in which the AMOC potentially played a key role (e.g., 8.2 kyr event) and when the availability of paleo records is maximized.

Further advances on model–data comparison also rely on the definition of appropriate metrics for AMOC variability, which should be agreed upon by the different communities involved. In this sense, extending the use of models that are able to simulate the main paleoclimate tracers (e.g., carbon and oxygen isotope composition, neodymium, or other circulation tracers) is paramount to creating models that better represent proxy data. This would not only allow for more direct model–data comparisons but also help accurately evaluate AMOC variability in climate models. Models could, in turn, help identify AMOC-related fingerprints and, thus, isolate climate variables (e.g., upper-ocean temperature and/or salinity, sea surface height) and areas that can be potentially used to reconstruct its past changes (an example is highlighted in Figure 2). To complement and reinforce such proxy-based reconstructions, records of flow speed are an invaluable source of independent

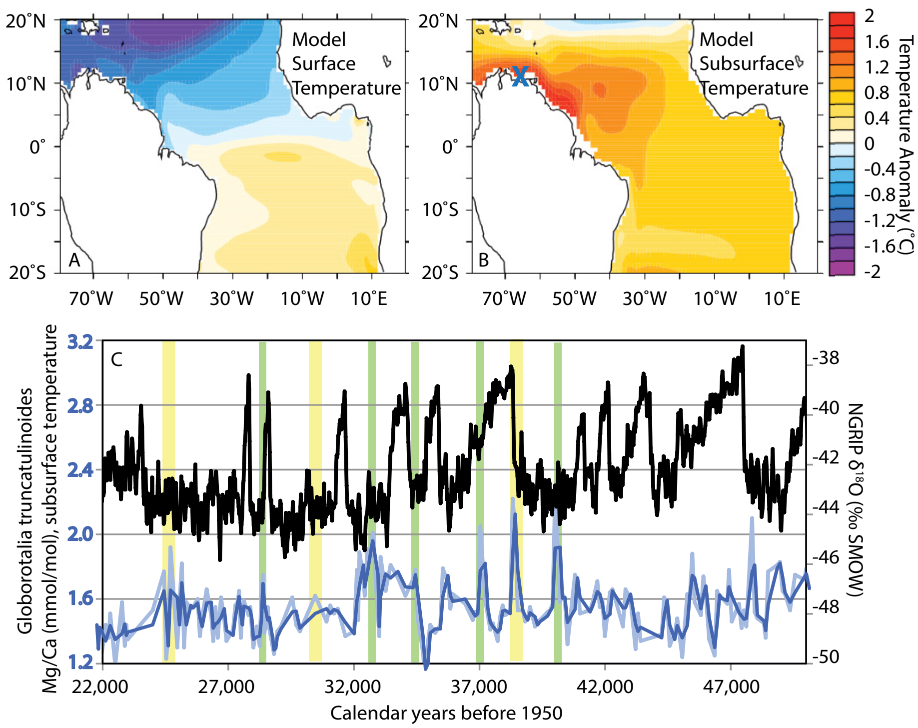

Figure 2: Temperature fingerprint of AMOC in GFDL CM2.1 water hosting experiment (Zhang 2007), SST anomalies (a) and 400 m depth (b). (c) Subsurface (200-400 m) temperature reconstruction from Bonaire Basin (blue X in b), based on foraminiferal Mg/Ca, showing a few degrees of warming associated with Dangaard-Oeschger events seen in the NGRIP ice $\delta^{18}O$ during the last glacial period (from Parker et al. 2015).

information, since they can also reflect AMOC changes. The verification of the flow speed in models is, nonetheless, still difficult, as it demands highly realistic bottom topography.

Ultimately, we agreed that more in-depth coordination of the proxy, observational, and modeling communities is essential to understand AMOC variability and its major drivers, a necessary step before assessing its real predictability.

Session 3: AMOC Impacts on Climate, Ecosystems, and Biogeochemistry

Impacts of AMOC on the Earth system can be categorized as direct and indirect. For example, AMOC variability has a direct impact on heat transport, sea surface temperature (SST), carbon uptake, and nutrients in various sectors of the Atlantic Ocean. In turn, these direct consequences, such as SST changes, can result in changing the characteristics of cyclones or tropical rainfall patterns. Thus, the latter two impacts could be categorized as indirect impacts of AMOC changes.

It became clear through the course of the discussion that rigorously categorizing the direct and indirect impacts of AMOC variability is not straightforward. We did, however, identify an emerging, consensus on priorities for observation systems and proxy reconstructions for these impacts. The discussion led to overarching recommendations for pathways to better characterize the impacts of AMOC variability.

We identified a list of direct impacts of AMOC variability on decadal and centennial timescales, along with potential methods to observe and reconstruct these parameters (Table 1). Heat transport, density, nutrients, ocean carbon and oxygen content, and sea level are included. We prioritized the Holocene period, and the last millennium (the Little Ice Age and Medieval Climate Anomaly in particular) as important targets for proxy reconstruction involving the aforementioned parameters. Although, other time periods where high-resolution reconstructions can be facilitated are also important targets, especially when independent evidence implicates AMOC changes (such as the 8.2 kyr event).

Table 1: Variables identified as directly impacted by AMOC variability along with the proxy and modern observational data types that provide information about them.

Variable	Proxies	Observations
Heat Transport	SST (assemblages, paired Mg/Ca-δ^{18}O in foraminifera, Sr/Ca in corals, alkenones, TEX86, etc.), subsurface temperature (thermocline and benthic paired Mg/Ca-δ^{18}O, deepwater corals)	Argo, World Ocean Atlas (WOA), Earth system models and assimilations
Density	Surface and subsurface salinity (δ^{18}O, δ^{18}Osw, deuterium in alkenones, dynocysts, Sr/Ca in corals, etc.)	Argo, WOA, Earth system models and assimilations
Nutrients	Cd/Ca, δ^{13}C, δ^{15}N, δ^{30}Si (indirect proxies for nutrient availability: Opal, C_{org}, biomarkers, barite)	Nitrate and phosphorous, silica, iron (WOA, GEOTRACES), Earth system models and assimilations
Carbon	B/Ca, δ^{11}B, U/Ca, δ^{13}C	pH measurements, CFCs, DIC, ^{14}C tracers, Global Ocean Data Assimilation Project (GLODAP), Biogeochemical (BGC)-Argo, Surface Ocean CO_2 Atlas (SOCAT), Earth system models and assimilations
Sea Level	Coral microatolls, foraminiferal assemblages in marshes	Altimetry, tide gauges

Indirect impacts are characterized as those that are “second order” impacts affected and influenced by the aforementioned parameters. Terrestrial carbon cycling and marine ecosystems are indirectly, but significantly, influenced by AMOC variability. Reconstructions pertaining to these systems would be useful in characterizing not only the extent of AMOC influence on biogeochemistry and food webs but also the potential linkages between different AMOC impacts. For example, AMOC-related changes in ocean temperatures are hypothesized to have altered plankton availability, thereby impacting cod fish populations over the last century. Sea-ice and land-ice changes are also significantly affected by changing heat transport and density (both direct AMOC impacts), though they can also have their own impacts on AMOC through buoyancy forcing. Proxy systems reconstructing sea-ice and land-ice can be useful in characterizing how the AMOC system interacts with and affects the cryosphere. Examples include lipid biomarkers of sea-ice diatoms, ice-rafted debris, diatom assemblages in sediment cores, sea salt Na^+ in ice cores, and exposure dating of terrestrial outcrops. Global hydroclimate changes, including shifts in the Intertropical Convergence Zone, extratropical moisture systems, and monsoonal systems, can be influenced by direct AMOC changes such as inter-hemispheric heat transport and, as such, are crucial to understand the climatic impact of changing AMOC variability on decadal-to-centennial timescales. Thus, observations and proxy measurements of hydroclimate will be useful in discerning AMOC impacts. Other indirect impacts of AMOC changes include changes in sea-level pressure, the North Atlantic Oscillation (NAO), extreme weather events (storminess, hurricanes, heat waves), and basin teleconnections (El Niño-Southern Oscillation (ENSO), Atlantic Multidecadal Variability, Pacific Decadal Oscillation). Continued observations, proxy reconstructions, and modeling of these systems will aid in delineating the potential impact of AMOC changes through various first-order impacts. We also emphasized the importance of focusing on causal relationships rather than simply correlative relationships. Initial focus should be on impacts for which there is already a robust mechanistic understanding and where AMOC has a dominant role, relative to other influences.

3 RECOMMENDATIONS

An underlying goal of the workshop is to improve our mechanistic understanding of AMOC, its drivers and impacts, in order to be able to make better predictions about the future. To do so, we need to put present day observations in longer-term context and be able to compare current observations and predictions of AMOC, including AMOC-related variables, to past behavior. The workshop participants identified four main strategies to move forward on this line of research:

1. Work toward a physically consistent framework between models and observations to enable comparisons between commensurate data;
2. Further develop proxy data to build a spatial network of AMOC and AMOC-related variables focused on the last 1000 years;
3. Improve our understanding and communication of the uncertainties in both proxy and model data; and
4. Encourage coordination between relevant scientific communities through formal and informal means.

Enabling a physically consistent framework between models and observations

During this workshop, we realized that the scientific community is limited by the ability to make comparisons between paleoclimate data, model data, and modern observations. Models often describe AMOC as the maximum amplitude of the zonally integrated stream function at a particular latitude, and modern observational networks have been set up with this in mind. However, paleoclimate proxy data is by definition not a direct measure of AMOC, making it difficult to integrate the data. Proxy records, more often than not, reconstruct only some AMOC-related variables, such as bottom water velocity in the area of the deep western boundary currents or vertical mixing in the Labrador Sea. The physical link to AMOC may be implied or assumed based on theory but is often not explicit or rigorously tested because of a lack of available data. Research activities that move the communities toward common standards for comparisons between observational and model data need to be prioritized.

We identified multiple potential strategies to address this priority. Encouraging and expanding ongoing efforts to incorporate proxy variables in Earth system models, especially oxygen and carbon isotopes, would enable direct comparisons of model output with measurements made in biogenic carbonates from marine geologic archives such as foraminifera, bivalves, and corals. Another strategy is to continue to promote the development of paleoenvironmental records that overlap with the instrumental data to provide a period over which rigorous proxy validation and calibration can occur. In addition, the paleoceanographic community should encourage the use of paleo data by other scientific communities, requiring a serious effort on the part of the community to compile, quality control, and provide estimates of uncertainty. The wide availability and uniformity of modern observational and model data provide good examples for the paleoceanographic community to work towards a similar standard. The PAGES 2k data compilation effort is an example of creating a uniform database of paleo data for use by the broader scientific community to facilitate model-data comparisons that will be particularly useful for CMIP6 last millennium experiment validation. Similar projects for other timescales could prove valuable as well. Furthermore, a new effort to assimilate paleoclimate proxy data into a model framework to construct a 1000-year reanalysis of the climate system, including AMOC-related metrics, is promising and potentially valuable for interpreting complex paleoclimate data signals into a cohesive history of the system, as well as improving our mechanistic understanding of the proxy evidence for AMOC variability. Such a scheme objectively accounts for proxy uncertainties, providing a best estimate of the evolution of the climate system based on data representing the actual evolution of the system, constrained by our understanding of the physics.

Further developing proxy data to build a spatial network of AMOC and AMOC-related ocean circulation focused on the last 1000 years

Iterating between observational data and models can be a powerful tool for improving mechanistic understanding of AMOC. Observations tell us how the system behaves, and models provide a tool to explore how such behavior arises. Conversely, if different models have different mechanisms, we can use observations to constrain which model might have a more realistic simulation of the process. Such data-model comparisons for AMOC require an improved network of proxy records that can characterize the spatial and temporal variability in the system, including the frequency and amplitude of decadal to centennial variability as well as the response in associated environmental variables.

The last 1000 years is a key target period for generating new AMOC-related reconstructions. It encompasses natural and anthropogenic eras, providing a test bed for teasing apart natural versus anthropogenically forced AMOC variability and enabling us to extend the instrumental records to address the potential links between AMOC and other system variables (e.g., North Atlantic SST anomalies, ITCZ location, NAO, ENSO, Pacific decadal variability). Studying AMOC over the last 1000 years has practical advantages too. Paleoclimate data is relatively abundant (providing information about background climate and other variables of interest), the climate forcing parameters are reasonably constrained, annual or better resolution proxy archives are available, and potential overlap with instrumental records provides an opportunity to quantitatively calibrate and validate proxy reconstructions.

Improving the network of proxy records needs to be guided by process-based information. The physical importance of the high latitudes (northern and southern) in the formation of deepwater and in setting the density structure of the Atlantic basin gives reconstructions from those regions high priority, especially Labrador Sea density, Nordic Seas overflow strength, and ventilation changes in the Southern Ocean. Reconstructing other key components of AMOC flow can be helpful too, such as Gulf Stream intensity, deep western boundary current flow, cross equatorial transport, and Agulhas leakage. Expansion of geostrophic flow reconstructions from foraminiferal $\delta^{18}O$-based density estimates would provide paleo reconstructions of AMOC flow that are physically based and could be directly used in data-model comparisons. Modeling work is needed to provide important guidance on optimal sampling sites and the adequacy of current data networks to represent variables of interest (OSSE or pseudo-proxy experiments). Further, modeling work can help identify AMOC fingerprints (e.g., SST or SSS anomalies in specific areas of the ocean) that can be explored in paleo data to improve AMOC reconstructions.

Dealing with uncertainty in proxies, observations, and model output

Cross-disciplinary coordination and cooperation could be better facilitated if we all make an effort to better quantify and report the uncertainties of our research. This issue came up repeatedly in reference to proxy reconstructions and calibrations, data assimilation and reanalysis projects, climate forcing factors used to drive models, and data-model comparisons. Two types of solutions are i) research focused on quantification and minimization of uncertainty, and ii) finding ways to better communicate known sources of uncertainty across disciplines. The latter is a matter of community awareness and individual effort, so we focus on the former in our recommendations.

To improve uncertainty estimates for paleoclimate observations, we recommend encouraging more research into proxy validation and calibration. This includes, but not limited to, investigating core top and sediment trap data to characterize modern climate signals, using overlap between instrumental and proxy datasets to verify and quantify physical relationships between measured and reconstructed variables, as well as developing networks of paleo data that enable identification of common signals and quantification of noise. In the long run, paleo data assimilation projects show promise for estimating past conditions while quantitatively accounting for proxy uncertainty. While the application of data assimilation techniques to paleo data is in its infancy and likely needs continued improvement of paleo observations to be useful, these efforts should be supported.

Differences in AMOC within and between free running dynamical models and data-constrained reanalysis models represent uncertainty in our physical understanding of AMOC processes as well as uncertainty in our ability to simulate the physical processes involved. Model intercomparison projects, such as CMIP, PMIP and CORE, provide an important first step to understand uncertainties in dynamical representations of Earth processes. Work to compare AMOC in ocean reanalysis models is similarly important. Such large cooperative projects provide vital information to potential model-data users about fundamental differences between models and the range of representations of AMOC. We recommend improving estimates of uncertainty in model forcing variables, such as ice-sheet variability, to help constrain models of past AMOC variability. As more paleo observations of AMOC and AMOC-related climate variability become available (with better quantified uncertainty bounds), we recommend focusing on evaluating models for their ability to represent the frequency, amplitude, and mechanisms behind decadal-scale AMOC processes in the observational data.

Improving coordination between paleo and modern communities to keep the momentum going

Coordination between the paleo and modern communities must be done at an organizational level to encourage and support efforts at the individual researcher level. One suggestion to provide this institutional impetus is to add a paleoceanographic-specific Task Team to the US AMOC/UK RAPID Science Teams. Integrating the paleo AMOC community into the US AMOC/UK RAPID programs will foster productive collaborative relationships and facilitate cross-disciplinary learning and understanding. We also suggest reviving something similar to the former PAGES-CLIVAR Intersections program to develop international near-term priorities and implement action items to encourage collaboration on specific topics. Links between CMIP and PMIP are considered important and worth strengthening to further improve coordination between the paleo and modern climate modeling communities. We also recommend individuals and organizations to organize webinars and virtual workshops to encourage collaboration on specific topics, and developing a catalogue and map of relevant modern and paleo datasets such as in Figure 1.

4 CONCLUSION

We brought together researchers working on AMOC at multiple timescales to find synergies and identify pathways forward to improve our understanding of AMOC. We had four goals at the outset, focused on exploring ways to merge modern and paleo perspectives to 1) reconstruct the history of AMOC variability, 2) test mechanistic hypothesis of AMOC, 3) identify AMOC impacts and fingerprints, as well as more generally 4) fostering collaboration between modern and paleo AMOC scientists. We worked towards these goals with presentations of the latest science and abundant time for formal and informal discussions. In the final session, about half the participants identified four primary recommendations that are outlined along with bulleted summaries of key points in Table 2 (next page). Three of the four recommendations address research priorities that will promote our understanding of AMOC. The fourth recommendation addresses ways to promote progress on these outstanding science questions through continued cross-disciplinary collaboration. Many participants felt the workshop represented an exciting push in a fruitful direction for AMOC research and are eager to continue the momentum.

Table 2. Summary of the four broad recommendations to come from this workshop with highlighted specific actions.

Recommendations	Actions
Develop a physically consistent framework between models and observations	• Define metrics for data-model comparison among models and observations, both paleo and modern • Standardize paleo data for use by scientists outside of the paleo community • Encourage development of proxies that overlap with the instrumental data to enable comparisons • Work towards a paleo AMOC reanalysis project that assimilates paleo proxy data into models to reconstruct spatially-coherent timeseries for the past 1,000 years

Further develop proxy data to build a spatial network of AMOC and AMOC-related ocean circulation focused on the last 1000 years	• Develop proxies for the last 1000 yrs, guided by model/mechanistic fingerprints and drivers of AMOC, for example:
	  ▫ LSW density, overflow, Southern Ocean changes (ventilation, Agulhas leakage)
	  ▫ Other potential drivers/indicators of the above variables (e.g. ice-related variables, SST anomalies, SSS anomalies)
	  ▫ Testing the connection between AMOC and SST
	• Utilize depth transects of foraminiferal $\delta^{18}O$, which could give more nuanced understanding of water column density changes and geostrophic flow strength
	• Characterize the decadal variability in proxy records (frequency, amplitude, mechanisms)

Deal with uncertainty in proxies, observations, and model output	• Quantify uncertainties in proxy and modern data reconstructions, including oceanic and atmospheric reanalysis products • Estimate uncertainty in forcings, such as ice sheet variability • Evaluate models with the decadal variability (frequency, amplitude, mechanisms) found in observations (emerging constraints)
Improve coordination between paleo and modern communities to keep the momentum going	• Establish a paleo AMOC-focused Task Team within the US AMOC and UK RAPID programs • Reinvent a PAGES-CLIVAR Intersections-like international work group • Strengthen links between PMIP and CMIP • Organize webinars and virtual workshops to encourage collaboration on specific topics • Develop a catalogue and map of relevant modern and paleo datasets

5 ACKNOWLEDGEMENTS

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- NSF Marine Geology and Geophysics Program
- Past Global Changes (PAGES)

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Appendix A: List of Participants

Name	Institution
Burls, Natalie	George Mason University
Chandiran, Siva	Bharathidasan University
Condron, Alan	University Massachusetts, Amherst
Danabasoglu, Gokhan	National Center for Atmospheric Research
Gebbie, Geoffrey	Woods Hole Oceanographic Institution
Gill, Emily	University of Colorado Boulder
Hall, Ian	Cardiff University
Hu, Aixue	National Center for Atmospheric Research
Ivanovic, Ruza	University of Leeds
Jaccard, Samuel	University of Bern
Jahn, Alexandra	University of Colorado Boulder
Killbourne, K. Halimenda	University of Maryland Center for Environmental Sciences
Kim, Who	National Center for Atmospheric Research
Klockmann, Marlene	Max-Planck-Institute for Meteorology
Kwon, Young-Oh	Woods Hole Oceanographic Institution
Lehman, Scott	University of Colorado, Boulder
Li, Jianping	Beijing Normal University
Lippold, Jörg	University of Bern
Little, Christopher	Atmospheric and Environmental Research, Inc
Liu, Wei	Scripps Institution of Oceanography, UC San Diego
Lloren, Ronald	The Marine Science Institute
Lozier, Susan	Duke University
Lucas, Sandy	NOAA Climate Program Office
Lund, David	University of Connecticut
Marchitto, Tom	University of Colorado Boulder
McCave, Nick	Cambridge University
Mette, Madelyn	Iowa State University
Moffa Sanchez, Paola	Rutgers University
Moreno-Chamarro, Eduardo	Max Planck Institute for Meteorology
Morrill, Carrie	University of Colorado and NOAA
Ninnemann, Ulysses	University of Bergen & Bjerknes Centre for Climate Research
Nye, Janet	Stony Brook University
Omta, Anne Willem	Massachusetts Institute of Technology
Oppo, Delia	Woods Hole Oceanographic Institution
Ortega, Pablo	NCAS Climate/University of Reading

Patterson, Michael	US CLIVAR Project Office
Reisdorf, Jill	University Corporation for Atmospheric Research
Repschlaeger, Janne	Kiel University
Richey, Julie	US Geological Survey
Robson, Jon	NCAS-Climate, University of Reading
Romanou, Anastasia	NASA/Goddard Institute for Space Studies
Saenger, Casey	University of Washington
Saleem Arrigo, Jennifer	NOAA Climate Program Office
Schloesser, Fabian	University of Hawaii
Schmittner, Andreas	Oregon State University
Sentman, Lori	NOAA Geophysical Fluid Dynamics Laboratory
Slawinska, Joanna	Rutgers University
Srokosz, Meric	National Oceanography Centre
Swingedouw, Didier	French National Center for Scientific Research
Szuts, Zoltan B	University of Washington
Thirumalai, Kaustubh	University of Texas at Austin
Thomas, Matthew	Yale University
Thornalley, David	University College London
Tjiputra, Jerry	Uni Research
Todd, Jim	NOAA Climate Program Office
Uhlenbrock, Kristan	US CLIVAR Project Office
Wainer, Ilana	University of Sao Paulo
Wanamaker, Alan	Iowa State University
Weijer, Wilbert	Los Alamos National Laboratory
White, Michael	Nature Publishing
Whitney, Nina	Iowa State University
Yeager, Stephen G	National Center for Atmospheric Research
Zhang, Rong	NOAA Geophysical Fluid Dynamics Laboratory

Appendix B: Agenda

Monday, May 23, 2016

08:45 Welcome remarks Hali Kilbourne, U. Maryland

Session I: AMOC State and Variability

09:00 Our current understanding of the AMOC and its variability: The modern ocean view
Susan Lozier, Duke U.

09:20 Decadal-to-millennial scale variability in deep components of the AMOC: A recent exceptional weakening?
David Thornalley, U. College London

09:45 Lightning Talks: Group I

Jörg Lippold, University of Bern
Chris Little, AER
David Lund, University of Connecticut
Siva Chandiran, Bharathidasan University
Tom Marchitto, University of Colorado Boulder
Anne Willem Omta, Massachusetts Institute of Technology
Pablo Ortega, University of Reading
Janne Repschlaeger, Kiel University
Lori Sentman, NOAA Geophysical Fluid Dynamics Laboratory
Kaustubh Thirumalai, University of Texas at Austin
Jerry Tjiputra, Uni Research

10:45 Break

11:00 Poster Session I

12:30 Lunch

14:00 AMOC State and Variability Summary and Discussion: Bridging the gaps between modern and paleo observations of AMOC

Session II: AMOC Mechanisms and Predictability

15:00 Mechanisms associated with predictable North Atlantic variability
Steve Yeager, NCAR

15:20 Natural variability in Nordic Seas overflows: Toward a mechanistic understanding of proxy records
Ulysses Ninnemann, U. Bergen

15:45 Break

16:00 Lightning Talks II

Alan Condron, University of Massachusetts Amherst
Aixue Hu, National Center for Atmospheric Research
Alexandra Jahn, University of Colorado Boulder
Marlene Klockmann, Max Planck Institute for Meteorology
Young-Oh Kwon, Woods Hole Oceanographic Institution
Jianping Li, Beijing Normal University
Wei Liu, Scripps Institution of Oceanography
Eduardo Moreno-Chamarro, Max Planck Institute for Meteorology
Carrie Morrill, University of Colorado and NOAA
Fabian Schloesser, University of Hawaii
Andreas Schmittner, Oregon State University

17:15 Networking event

Tuesday, May 24, 2016

Session II: AMOC Mechanisms and Predictability continued

08:30 Poster Session II

10:00 Break

10:15 AMOC Mechanisms and Predictability Summary and Discussion: Testing ideas about the drivers of AMOC variability on multidecadal to millennial timescales

Session III: AMOC Impacts on Climate, Ecosystems, and Biogeochemistry

11:15 AMOC Impacts on Climate
Rong Zhang, NOAA GFDL

11:35 AMOC Impacts on the Carbon Cycle and Atmospheric CO_2
Andreas Schmittner, Oregon State U.

11:55 The role of basin-scale oceanographic processes on the abundance and distribution of North Atlantic fish stocks
Janet Nye, SUNY Stony Brook

12:15 Lunch

13:30 Lightning Talks: Group III

Natalie Burls, George Mason University
Geoffrey Gebbie, Woods Hole Oceanographic Institution
Emily Gill, University of Colorado, Boulder
Ian Hall, Cardiff University
Samuel Jaccard, University of Bern
Nick McCave, Cambridge University
Madelyn Mette, Iowa State University
Paola Moffa Sanchez, Rutgers University
Jon Robson, University of Reading
Didier Swingedouw, French National Centre for Scientific Research
Zoltan Szuts, University of Washington
Matthew Thomas, Yale University
Nina Whitney, Iowa State University

14:30 Poster Session III

15:45 Break

16:00 AMOC Impacts on Climate, Ecosystems, and Biogeochemistry Summary and Discussion: Linkages between AMOC and other Earth system processes

Wednesday, May 25, 2016

09:00 Breakout Groups

Breakout Group 1: AMOC observations, state and variability. They will explore ways to optimize paleo-observational networks to ensure reliable AMOC reconstructions over relevant timescales.

Breakout Group 2: AMOC Mechanisms and Predictability will focus on how paleoceanographic and paleoclimatic data can be used to test proposed AMOC mechanisms and predictability.

Breakout Group 3: Climate Sensitivity to AMOC: Climate/Ecosystem Impacts will focus on merging the evidence for AMOC impacts on the Earth system from modern and paleo data.

10:30 Break

11:00 Final discussion and breakout group summaries

12:30 Lunch

14:00 (Optional) Writing and planning session to summarize the results of the workshop

16:00 End of workshop

US Climate Variability &
Predictability Program
1201 New York Ave NW, Suite 400
Washington, DC 20005
www.usclivar.org
uscpo@usclivar.org
twitter.com/usclivar

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