BIBLIOGRAPHIC CITATION

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US AMOC Science Team at the May 2017 meeting in Santa Fe, New Mexico.
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EXECUTIVE SUMMARY

The US AMOC program was established in 2008 to develop an improved understanding of the Atlantic Meridional Overturning Circulation (AMOC) and implement components of an AMOC monitoring system and prediction capability. The US AMOC Science Team, comprised of funded investigators, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies (NSF, NOAA, NASA, and DOE). The report herein is the ninth progress report submitted by the US AMOC Science Team. The purpose of this report is to summarize progress on the main objectives of the program, identify any new programmatic gaps, and provide near- and long-term research priorities and objectives for the program, since the 2016 report.

The Science Team held a very successful meeting in Santa Fe, New Mexico, during May 2017. It brought together over 80 researchers to identify emerging research gaps and questions, provide updates on progress within the community, and discuss future opportunities and legacy activities as the Science Team plans to wrap-up in 2020. The meeting featured two topical special science sessions intended to address open questions within the community. The first session on the Atlantic Multidecadal Variability (AMV) provided an opportunity to discuss the relative contributions of ocean dynamics and stochastic atmospheric forcing to the creation and driving of the AMV. The second special session was on AMOC stability metrics, reviewing the state of knowledge and discussing new results regarding the role of AMOC-induced freshwater flux into the Atlantic on the stability of the AMOC. In addition to the Santa Fe Meeting, members of the Science Team organized two AMOC-themed sessions at the 2018 Ocean Sciences Meeting in Portland, Oregon. Many Science Team members presented their findings in these two sessions, as well as in several other relevant sessions.

Since the 2016 report, a major effort of the Science Team has been (and continues to be) planning for legacy products leading up to the program sunset in 2020. One of our primary activities is a set of review and synthesis papers published as part of a virtual special collection in AGU journals in late 2018. This effort is in collaboration with international colleagues, especially with the UK RAPID program. Additional sunset activities are being outlined by the Executive Committee.

Activities within the US AMOC program continue to be organized under Task Teams.

1. AMOC observing system implementation and evaluation
2. An assessment of AMOC state, variability, and change
3. An assessment of AMOC variability mechanisms and predictability
4. An assessment of the role of AMOC in global climate and ecosystems
In 2018, a new Task Team is being formed to enable and improve cross-disciplinary collaborations between the paleo and modern oceanographic communities, bringing the number of Task Teams to five. This new Paleo AMOC Task Team, to be comprised of paleo and modern AMOC scientists, will complement the existing four Task Teams with a focus on AMOC variability and changes across decadal to centennial timescales, including past shifts in the AMOC.

Progress on these main program objectives is summarized in Section 2. A few highlights of these recent accomplishments are listed below.

- Underpinned by the rich dataset being collected by the observational network, which includes trans-basin arrays at multiple latitudes, our understanding of AMOC variability and the underlying dynamics continues to progress. The duration of some records has reached sufficient length to identify decadal-scale variability embedded in the strong high-frequency variability including: (i) a decrease in the meridional heat transport at 26.5°N, (ii) a decrease in the equatorward transport of some DWBC components, (iii) no statistically significant trend in Gulf Stream strength, and (iv) evidence for a lack of MOC coherence across some latitudes within the subtropical gyre.
- Observations from the newest trans-basin array (OSNAP) have changed our view of classical overflow pathways. Furthermore, meridional heat transport is found to be correlated with the strength of the MOC, while meridional freshwater transport is not.
- Results using ocean reanalyses, models, and observations show that Atlantic gyre variability at interannual and decadal periods can be described as gyre spin up and spin down. This has been found recently for the South Atlantic subtropical gyre, in addition to previous findings for the North Atlantic subtropical and subpolar gyres and their intergyre coherence. Gyre strength, AMOC/SAMOC, and meridional heat transport are related throughout the Atlantic basin.
- Observational and modeling studies find that the lower limb of the AMOC, from the subpolar to the subtropical North Atlantic, is coherent for the deepest layer, but that the mid and upper layers are related to Gulf Stream position. The boundary between gyres that includes nearby recirculations regions, the Western Transition Zone, is closely related to the strength of intergyre export and to heat transport convergences, which in turn drive ocean heat content anomalies.
- High-resolution regional- and basin-scale models have been used to study mixing and air-sea exchange in key regions, such as the Gulf Stream/North Atlantic Current, Denmark Strait, the Labrador Sea, the Brazil Confluence region, and fjords on the east Greenland shelf.
- Analysis of ensemble coupled model runs and reanalysis products have shed light on the role of AMOC in low-frequency climate variability as represented by SST, heat content, heat transport, and sea ice cover.
- Yet the relative roles of external forcing (e.g., aerosols), atmospheric forcing, and ocean dynamics in setting the Atlantic Multidecadal Variability (AMV) continue to be vigorously debated. It is now understood that the importance of the AMOC in setting SST and ocean heat content must be assessed in comparison to other processes, including changes in the wind-driven gyre circulation.
- There are two-way interactions between the AMOC and the cryosphere. Although AMOC declines in CMIP5 models are mostly due to warming, new results suggest that melting of ice
sheets leads to further weakening of the AMOC. Research suggests that recent changes in Arctic sea ice are related to changes in ocean heat transport rather than external forcing.

The Task Team 3 webinar series continues to be a very effective venue for quick and timely exchange of scientific findings, fostering collaborative discussions of priority science questions. While the prior series was organized around the influences of freshwater on AMOC, in 2017 the subject area was broadened to the overarching topic area of mechanisms of AMOC variability and predictability. Recordings of the previous webinars can be viewed on the US CLIVAR YouTube channel.

The near- and long-term priorities for the program are presented in Section 3, including updates since the 2016 report, some emerging science questions, and better articulation of existing objectives. These priorities remain largely unchanged from those of the 2016 report. Section 4 summarizes observational, paleo-proxy, and modeling activities to maintain in order to achieve both near- and long-term goals. These activities are also very similar in content to the previous reports, emphasizing the ongoing importance of enabling infrastructure.

The US AMOC Science Team provides a unique opportunity to exchange ideas and explore collaborations among scientists studying modern observations, paleo proxies, climate modeling, and the impacts. We believe that such synergistic activities should continue to be strongly encouraged and supported.
INTRODUCTION

The US Atlantic Meridional Overturning Circulation (AMOC) Program, a component of the US Climate Variability and Predictability (CLIVAR) Program, was initiated in 2008 to increase understanding of AMOC variability, mechanisms, and impacts; develop and implement an AMOC monitoring system; and establish an AMOC prediction capability. A Science Team was established in the first year to foster communication and collaboration among individuals with US agency-funded research projects. Comprised of PIs, co-Is, postdocs, and students, the Science Team sets and accomplishes the program goals, objectives, and priorities, with guidance and oversight from the sponsoring agencies. As one of its responsibilities, the Science Team produces reports that are intended to i) facilitate the dissemination of recent research results; ii) help the agencies as well as the scientific community identify gaps in our understanding and measurement of the AMOC; iii) identify and document near- and long-term research priorities and goals; and iv) aid the coordination of efforts across agencies. A further aim of the progress reports is to provide concise and timely communication to international collaborators on the US AMOC efforts, including the identification of evolving monitoring, modeling, and science issues.

The report herein is the ninth report submitted by the US AMOC Science Team. It describes the progress made over the 18 months from July 2016 through December 2017 in the four (existing) major areas of focus within the program. Appendices provide the current membership and charge for each Task Team, a list of current projects supported by sponsoring agencies, and brief individual project reports. The next, and final report, for the Science Team will serve as a capstone for the term of the Science Team.

Now a decade after initiation, the Science Team remains robust and includes 79 members working on 63 projects supported by NSF, NOAA, NASA, and DOE. Planning activities within the US AMOC program continue to be organized under Task Teams, consisting of Science Team members, each led by a chair and vice-chair. In 2018, a new fifth Task Team is being formed to better enable cross-disciplinary collaborations between the paleo and modern oceanographic communities working on AMOC across decadal to centennial timescales, including past shifts in the AMOC. Outreach has been conducted with funding agencies on projects to be invited to join this new Task Team. In 2018, the Task Team will be officially started and a chair and vice-chair will be selected. Integration of the new Task Team will be a priority as the Science Team considers creating a robust legacy of research topics and priorities for the community to continue after 2020.

The Task Team leaders, together with the Science Team chair, form the US AMOC Executive Committee. Following the protocol established in 2013, the Executive Committee selects Task Team leaders from the nominations provided by the Science Team. A list of current leadership positions is as follows:
Science Team Chair: Gokhan Danabasoglu

Task Team 1: AMOC Observing System Implementation and Evaluation
Chair: Magdalena Andres; Vice-chair: Kathleen Donohue

Task Team 2: AMOC State, Variability, and Change
Chair: Zoltan Szuts; Vice-chair: Claudia Schmid

Task Team 3: AMOC Mechanisms and Predictability
Chair: Mike Spall; Vice-chair: Aixue Hu

Task Team 4: Climate Sensitivity to AMOC: Climate/Ecosystem Impacts
Chair: Martha Buckley; Vice-chair: Chris Little

Task Team 5: Paleo AMOC
(being established)

The US AMOC Executive Committee provides overall program guidance and liaises with the US CLIVAR Project Office and agency program managers. Specific terms of reference describing the roles of the Task Teams in helping to coordinate research in these five areas are listed in Appendix A, along with the current membership.

The Science Team has held regular meetings since 2009. In 2011, 2013, and 2015, these meetings were jointly organized with the UK RAPID program as science conferences open to the international community. The next international science conference will be held during 24–27 July 2018 in Miami, Florida, and is being chaired by Renellys Perez (NOAA AOML).

The most recent US AMOC Science Team meeting was held in 23–25 May 2017 in Sante Fe, New Mexico, and chaired by Wilbert Weijer (LANL). The meeting brought together over 80 researchers to provide updates on progress within the community, identify emerging research gaps and questions, and discuss future opportunities and legacy activities as the Science Team moves into its final phase toward sunset in 2020.

The meeting featured two topical special science sessions intended to address open questions within the community. The first session on the Atlantic Multidecadal Variability (AMV) provided an opportunity to discuss the relative contributions of ocean dynamics and stochastic atmospheric forcing to the creation and driving of the AMV. During the session, two contrasting views were presented and discussed. In one view, it is argued that the AMV is a direct response to the North Atlantic sea surface temperatures (SST) to atmospheric stochastic forcing and/or external radiative forcings because the SST anomaly pattern associated with the AMV can be largely reproduced by a slab ocean model, implying that the ocean dynamics do not play a major role in creating the AMV. In contrast, the second view argues for a prominent role for ocean dynamics. Specifically, this argument suggests that the observed AMV includes coherent multidecadal variations in Atlantic SST and salinity, upper ocean heat and salt contents, and ocean-driven surface turbulent heat fluxes. These key observed features cannot be explained as direct
responses to stochastic atmospheric forcing and/or external radiative forcings but are, instead, consistent with an important role for ocean dynamics. The amplitude of the AMV and associated multidecadal atmospheric variations, as well as its connection with the AMOC variability, are often underestimated in coupled climate model simulations, likely due to biases in models' mean state and in representations of modes of variability. Vivid and interesting discussions appreciated both views and generated ideas for future experiments that could help reconcile the competing conclusions.

The second special session was on AMOC stability metrics, which provided an opportunity to review the state of knowledge and discuss new results regarding the role of AMOC-induced freshwater flux into the Atlantic (mostly across its southern boundary at 35°S) on the stability of the AMOC. Commonly referred to as Fov, this freshwater flux is thought to be an indicator of whether the AMOC is in a mono-stable state (hence stable to finite-amplitude perturbations) or in a bi-stable state (hence prone to collapse, if perturbed strongly enough). The accuracy of this metric in models is rather surprising given that its fundamentals are captured by simple box models. One presentation discussed to what extent the assumptions in these box models carry over to comprehensive circulation models. It was suggested that the stability of the AMOC in the current generation of coupled climate models may be overestimated, due to common biases in the salinity field of the South Atlantic. A flux-correction was suggested as a specific solution to reduce this bias and make the stability of the AMOC in climate models more realistic. But the discussion naturally turned to the actual causes of the salinity bias, as biases in tropical precipitation were cited, as well as misrepresentation of Agulhas Leakage. It is generally thought that the move towards higher resolution models will reduce some of the biases seen in low-resolution models, and several studies were presented that probe the AMOC response to freshwater forcing in models that explicitly represent eddies. Indeed, new results showed that the AMOC is prone to collapse in an eddy-permitting model, suggesting that spatial resolution may affect the processes that influence the stability of the AMOC, although it is too early to say why.

A major outcome of the meeting was a proposed set of review and synthesis papers, summarizing advances in understanding of the AMOC that have emerged over the past decade of the Science Team and identifying ongoing challenges to be addressed. Since then, the list of review papers and authors has evolved and expanded in collaboration with UK RAPID program and other scientists internationally (Table 1). The papers, now being drafted, will be submitted to a virtual collection in AGU journals in 2018.

At the 2018 Ocean Sciences Meeting, held February 2018 in Portland, Oregon, there were two AMOC-themed sessions organized by the Science Team members: i) Atlantic Meridional Overturning Circulation: Modeling and Observations; and ii) Meridional Overturning Circulation Dynamics in Past Warm and Cold Climates. These sessions focused on the modern and paleo perspectives, respectively.

As the Science Team comes to completion at the end of 2020, the Executive Committee, Task Teams, and Project Office will be executing actions to transition the team to sunset. A preliminary set of activities is provided in Section 6 of this report.
Table 1: Proposed papers for an AMOC special collection in AGU journals.

<table>
<thead>
<tr>
<th>Paper Topic</th>
<th>Lead Author</th>
<th>Co-Lead</th>
<th>Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Observing the Atlantic Meridional Overturning Circulation: Pathways, Fluxes, and Transformation</td>
<td>Stuart Cunningham</td>
<td></td>
<td>Review of Geophysics</td>
</tr>
<tr>
<td>2 Linkage between the AMOC variability and the AMV and associated climate impacts, including both modern and paleo observational linkages</td>
<td>Rong Zhang</td>
<td></td>
<td>Review of Geophysics</td>
</tr>
<tr>
<td>3 Technological advances and novel approaches to existing and emerging data (and technologies) for sustainable AMOC observations</td>
<td>Gerard McCarthy</td>
<td></td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>4 Pathways of the Atlantic Meridional Overturning Circulation</td>
<td>Susan Lozier</td>
<td>Amy Bower</td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>5 AMOC stability, particularly focusing on the role of freshwater transport across 30°S</td>
<td>Wilbert Weijer</td>
<td>Sybren Drijfhout</td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>6 High-resolution models of the AMOC, including regional studies of key components such as the Southern Ocean, Gulf Stream, Agulhas Leakage, and high-latitude convection regions</td>
<td>LuAnne Thompson</td>
<td>Xiaobiao Xu</td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>7 Reexaming linkages between the Atlantic Meridional Overturning Circulation and Eastern North American sea level</td>
<td>Chris Little</td>
<td>Chris Piecuch</td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>8 Impact of the AMOC on ocean tracers</td>
<td>Anand Gnanadesikan</td>
<td></td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>9 Intercomparison of reanalysis products</td>
<td>Laura Jackson</td>
<td></td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>10 Recent advances in theoretical modeling of the AMOC</td>
<td>Helen Johnson</td>
<td>David Marshall</td>
<td>JGR-Oceans</td>
</tr>
<tr>
<td>11 North Atlantic variability across the last millennium: A review</td>
<td>Paolo Moffa Sanchez</td>
<td>David Reynolds</td>
<td>Paleoceanography/Climatology</td>
</tr>
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2 PROGRESS ON PROGRAM OBJECTIVES

2.1 Existing and approved observational programs

Implementation of a robust observing system in the Atlantic Ocean underpins the community's efforts to increase AMOC understanding — a key goal of Task Team 1. A rich dataset is being acquired through continuation and expansion of key components of the existing observational network (2.1.1) and through implementation of new technologies within the Atlantic array (2.1.2). Access to these ongoing data sources — coupled with analysis of observations from the completed measurement programs (2.1.3) — continues to enable and advance characterization of AMOC variability on seasonal-to-decadal timescales and moves us closer to the goal of improved understanding of AMOC dynamics. Ultimately, this will lead to better climate simulations and improved skill in seasonal-to-decadal forecasts. The success of the Atlantic observing system also depends critically on links with international partners. Elements of those AMOC observational programs that are US-funded and key results from analysis of AMOC observations are described below.

2.1.1 Ongoing measurement programs

From north to south, the ongoing measurement efforts in the Atlantic include the following programs.

“OSNAP: Overturning in the Subpolar North Atlantic Program” (Lozier, Johns, Bower, Pickart, and Straneo) is a US-led international program. OSNAP provides a continuous record of the full-water column, trans-basin fluxes of heat, mass, and freshwater in the subpolar North Atlantic through three components: OSNAP East, OSNAP West, and OSNAP floats. Measurements began in 2014. This ambitious effort coordinates a host of related research projects. Preliminary assessment of the earliest 21-month period of data provide an estimate of the meridional overturning circulation (MOC), including its variability and structure. Initial findings suggest that meridional heat transport (MHT) and MOC are correlated, yet meridional freshwater transport and MOC are not. OSNAP floats suggest major revisions to classic overflow pathway schematics. The Charlie Gibbs Fracture Zone (CGFZ) may not be the gateway for Iceland Scotland Overflow Water (ISOW) from the Iceland to Irminger Basin. ISOW floats appear to reach the Iceland Basin through deep gaps in the Reykjanes Ridge north of the CGFZ. Moreover, ISOW floats move west-northwestward toward the Labrador Sea or southwestward-southward along the western flank of the Mid-Atlantic Ridge rather than turning northward into the Irminger Basin. Moored arrays near Cape Farewell distinguish coastal Arctic origin and along-slope Greenlandic glacier freshwater inputs, thereby clarifying their seasonal variability.
“The Norröna Project: An International Collaboration for Sustained Studies of the Meridional Overturning Circulation between Denmark, the Faroes, and Iceland” (Rossby and Flagg) is a project that has been using an acoustic doppler current profiler (ADCP) in the hull of the high-seas ferry Norröna since 2008. Analysis of the data, together with expendable bathythermograph (XBT) data, archived hydrographic data, and mooring data, is providing accurate estimates of volume, heat, and freshwater fluxes between the northeast Atlantic and the southern Nordic Seas.

“The Oleander Project: High-Resolution Observations of the Dynamic Ocean between New Jersey and Bermuda” (Rossby, Donohue, Flagg, O’Brien, and Curry) has been using a hull-mounted ADCP on the CMV Oleander since 1992 as well as monthly XBT data and thermosalinograph measurements to sample the western Atlantic continental shelf, Slope Sea, Gulf Stream, and northwestern Sargasso Sea. The most recent update of the time series derived from these measurements shows that there is still not a statistically significant decrease in Gulf Stream transport from 1993 through 2016. Data from the Oleander Project continue to be used by other groups for related analyses.

“Western Boundary Time Series (WBTS) in the Atlantic Ocean” (Baringer, Meinen, and Garzoli) continues to measure the Florida Current near 27°N, which has been monitored nearly continuously at high temporal resolution since 1982. A line of bottom moored instruments has monitored the DWBC since 2004. The time series demonstrate the strong variability at timescales from daily to monthly, and they are becoming long enough to identify decadal variability and long-term trends embedded in this higher frequency variability. The WBTS data are easily accessible in near real-time and used by many groups. The synergy between WBTS and RAPID/MOCHA measurements is a critical component of the Atlantic observing system.

“Measuring Interannual Variability of the AMOC and Meridional Ocean Heat Transport at 26.5°N: The RAPID-MOCHA Array” (Johns, Meinen, and Baringer) has been continuously monitoring the strength and structure of the AMOC and MHT using a basin-wide observing system for 13 years and is funded to continue through at least 2020. Recent analysis shows that the MHT decreased from 1.33±0.05 PW for 2004-2008 to 1.17±0.07 PW for 2011–2015, consistent with a decrease in AMOC between the two periods.

“MOVE: Meridional Overturning Variability Experiment” (Send and Lankhorst) is a program that has maintained an operational observing system to continuously sample the strength of the lower branch of the AMOC at 16°N since 2000. The system includes records from moorings and sea floor instruments and extends from the western boundary near Guadeloupe to the Mid-Atlantic Ridge. Salinity observations from MOVE have helped identify the arrival of a fresher Denmark Strait Overflow Water (DSOW) at 16°N. In addition, the AMOC strength, as measured by MOVE, does not always track what is reported for 26.5°N by the RAPID-MOCHA Array. This discrepancy is a current area of investigation.

The “Southwest Atlantic MOC (“SAM”)” (Meinen, Garzoli, Perez, and Dong) project is designed to measure both the warm upper and cold deeper MOC flows near the South Atlantic western boundary at 34.5°S. The SAM array started in 2009 and serves as the cornerstone for an international trans-basin MOC array, called the South Atlantic MOC Basin-wide Array (SAMBA).
Results show strong offshore recirculation adjacent to the DWBC and a finding is that DWBC transport is highly variable due to remotely generated signals propagating into the boundary.

The “Ship of Opportunity Program” (Goni, Baringer, and Garzoli) has been providing critical measures of temperature profiles along repeat XBT lines throughout the Atlantic basin. This program partners with the Oleander Project to enable the measurements along the New Jersey-Bermuda transect across the shelf, slope, Gulf Stream, and western Sargasso Sea. Notably, these measurements sample the shelf-slope regions missed by the global ARGO array.

### 2.1.2 Technological development

“Comparison of Deepglider and RAPID-MOCHA Moored Array Observations” (Eriksen) uses gliders to collect full-depth temperature, salinity, dissolved oxygen, and depth-averaged current repeat sections across the western boundary current system. Early results show remarkably close correspondence between absolute geostrophic current estimates from Deepglider and those from a contemporaneous estimate from shipboard lowered-ADCP. The project successfully identified and solved technical and logistics challenges and demonstrated the merit of using autonomous underwater gliders to monitor the AMOC.

Building on the ongoing measurement program described above for the Oleander Project (Rossby, Donohue, Flagg, O’Brien, and Curry), 38 kHz and 75 kHz ADCPs are being incorporated into the new replacement vessel. This will provide high vertical resolution over the slope and will enable velocity measurements to about 1000 m depth (with the 38 kHz unit). These deep-reaching observations of Gulf Stream velocity, in combination with the collocated XBTs, will provide a robust measure of Gulf Stream heat transport.

### 2.1.3 Analysis of data from the Atlantic Observing System

“Pathways to the Denmark Strait Overflow: A Lagrangian Study in the Iceland Sea” (de Jong, Soiland, and Bower) uses acoustically tracked RAFOS (the word SOFAR spelled backwards with SOFAR as an acronym for SOund Fixing And Ranging) floats deployed in the Iceland Sea to elucidate the circulation of dense waters that supply overflow water to the Denmark Strait and Iceland-Faroe overflows. Interestingly, and contrary to expectations, entrainment of dense water into the North Icelandic Jet (NIJ), which connects the Iceland Sea east of the Kolbeinsey Ridge to the Denmark Strait sill, was not observed by the floats in this experiment. Model data will be used next to provide context for the float experiment and to examine whether this result might be due to atmospheric conditions during the experiment, which were not favorable to a NIJ pathway for dense waters.

“Completing a 10-Year Record of Deep Western Boundary Current Observations at Line W: A Contribution to the AMOC Study” (Toole, Andres, Curry, Joyce, McCartney, Smethie, and Le Bras) was designed to observe interannual water property variability and transport changes in the North Atlantic’s DWBC and Gulf Stream. Data from the sustained moored array and repeated occupation of the hydrographic section provided a 10-year time series of boundary current variability and was completed in 2014. A statistically significant trend of decreasing equatorward
transport was observed in several of the DWBC components as well as the current as a whole, with the largest linear change of 4% decrease per year in the layer of Labrador Sea Water that was renewed by deep convection in the early 1990s. Furthermore, water mass changes consistent with changes in source water properties upstream were observed with the arrival of waters with record cold, fresh, and low potential vorticity anomalies at Line W three to seven years after its formation in the Labrador Sea. Stirring between the DWBC and the abyssal interior was observed to coincide with deep cyclogenesis under Gulf Stream meander troughs.

“South Atlantic-North Atlantic Meridional Overturning Circulation (MOC) Linkages: Analysis of the Upper and Lower Limbs With In Situ Instruments” (Meinen, Perez, and Le Hénaff) is an ongoing analysis of in situ observations from moored arrays along 34.5°S in the South Atlantic (including NOAA’s SAM project) and along 26.5°N in the North Atlantic (including NOAA’s WBTS project), and data from the national and international partners at both latitudes. The overall goal of this project is to advance understanding of the temporal variability and meridional coherence of the upper and lower AMOC limb pathways in the South and North Atlantic.

“Variability of the South Atlantic Subtropical Gyre” (Perez) continues to investigate the time-variability of the South Atlantic subtropical gyre through analysis and interpretation of satellite and in situ data, synthesis products, and ocean-only and coupled climate data assimilation models.

### 2.2 AMOC State, Variability and Change

Task Team 2 bridges the gap between modeling studies and observations in order to develop a deeper understanding of the observable historical record and its variability. Before the RAPID project started to continuously measure overturning transport in 2004, overturning circulation was considered to be spatially coherent, basin-wide, and slow. In a review of the concept of the AMOC, Lozier (2016) contrasted these expectations with the limited supporting observational evidence found since 2004. High variability, short correlation scales, and multiple processes obscure underlying broad-scale patterns. Overall, the projects in Task Team 2 investigate this separation of scales between regions, observational systems, and modeling approaches.

With a focus on the past 50 years of AMOC evolution — the observable historical record — Task Team 2 investigates mechanisms and pathways that identify and explain coherent and incoherent signals. A goal is to reach consensus on which signals represent the large-scale AMOC versus more localized circulation patterns. As a team, discussions are being organized around three guiding questions:

- Which AMOC signals have been consistently identified in both observations and simulations, and which have not?
- What AMOC fingerprints show up coherently across multiple observing systems?
- What ideas drive us to consensus in data-assimilating models on current and past states of AMOC?

Consistent (robust) results are presented in this section, considering the second and third questions jointly, while nonrobust results provide a framework for future studies as discussed in section 3.2. This section emphasizes results obtained since the last US AMOC report for the following projects:
• “The Western Transition Zone as a Gatekeeper for the North Atlantic MOC Throughput” (Buckley, Lozier)
• “Fingerprints of AMOC Variations Derived From Machine Learning Methods” (DelSole, Klinger, Banerjee)
• “State of the Climate: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean” (Dong, Baringer, Goni, Garzoli)
• “Assessment of the Meridional Overturning Circulation and Meridional Heat Transport and their Meridional Variability in the South Atlantic Ocean” (Goni, Dong)
• “Diagnosing Overturning and Water Mass Transformation in the Labrador Sea From Argo Floats” (Holte, Straneo)
• “South Atlantic Meridional Overturning Circulation: Pathways and Modes of Variability” (Perez, Matano, Garzoli)
• “The Atlantic Water Boundary Current in the Eastern Arctic: Composition, Transport, Variability and Dynamics” (Pickart)
• “Improved Estimates of Atlantic Meridional Circulation from Altimetry with Tracers, Drifters, Gliders and Argo Floats” (Rhines, Hakkinen)
• “Observed transports of the Meridional Overturning Circulation at several latitudes in the Atlantic” (Schmid, Halliwell)
• “Forced Transients in Water Mass Transformation and the Meridional Overturning” (Spall)
• “Ventilation of Denmark Strait Overflow Water in the Iceland and Greenland Seas” (Spall, Pickart)
• “Wave processes along 26°N” (Szuts, Martini)
• “Sources and Impacts of Variability of the Meridional Property Transports in the Atlantic Ocean” (Thompson, Kelly)

2.2.1 Which AMOC signals have been consistently identified in observations and simulations?

Towards the goal of a unified understanding of pan-Atlantic AMOC variability, much progress has been made on understanding individual components that participate in AMOC circulation. At the 2017 US AMOC meeting, the Task Team identified four clear results found for the AMOC system: i) meridional coherence is found within gyres from observations and models; ii) within the North Atlantic subtropical gyre, wind input of momentum is the main driver of subannual variability; iii) for the deep limb of the AMOC, some internal components are coherent within the limitations of few observed events to characterize interannual variability; and iv) surface expression of the AMOC has a longer record, and studies consistently find a horse-shoe shaped pattern of SST anomaly associated with AMV for multi-decadal periods. Project results since the last report provide detailed support for these conclusions.

For the upper limb of the AMOC, there are more time series now available from observational networks that enable finer spatial and horizontal resolution, and have expanded the coverage to the South Atlantic and subpolar North Atlantic. Repeated XBT lines across the Atlantic (Baringer et al. 2017) provide regular snapshots of MHT, which are made available online. Calculations based on ARGO profiles (Majumder et al. 2016), in conjunction with satellite measurements of winds and sea surface height (SSH), provide monthly estimates of overturning strength and MHT to 2000 m depth. AMOC and SST over the past 25 years are highly correlated at each latitude, and enable
a reconstruction back to 1870 based on SST reanalyses (Lopez et al. 2015). In the South Atlantic, Schmid and Majumder (2017) found that AMOC and MHT have the largest means at 30°S with slight decreases to the north and south. Subannual variability is dominated by the annual cycle. Long-term changes of MHT (Baringer et al. 2017) show no trend in the South Atlantic at 35°S, in contrast to a decreasing trend in the North Atlantic at 26°N and 41°N.

Kelly et al. (2016) performed an independent calculation from in situ and satellite data over the entire Atlantic basin and focused on interannual periods. They found that heat drives trends in AMOC over recent decades. This applies to the recent AMOC slowdown, as well as for heat transport convergence that drives ocean heat content anomalies in the recirculation gyres adjacent to the Gulf Stream and North Atlantic Current. In turn, storage of heat in the recirculation gyres drives air-sea heat exchanges on interannual timescales. Gulf Stream and AMOC have similar decreasing trends over the past decade, which resembles spatial structure of sea level changes reminiscent of mid-latitude wind-stress variability (increased SSH inshore of Gulf Stream, decreased SSH offshore; Zhang et al. 2016; Kelly et al. 2017). In more detail, the Gulf Stream strength is linked at 26°N and east of 64°W. The Gulf Stream is also linked with the deep limb, as an increase of upper mid-ocean flow is related to northward shifts of the Gulf Stream.

The lower limb at 26°N has previously been found to be correlated with AMOC, in terms of the lowest layer of southward return flow (lower North Atlantic Deep Water, NADW). To investigate this relation further, Buckley, Lozier, and Zou used modeling studies and found that AMOC is correlated with all of the deep water in the subpolar gyre but by extending into the subtropics correlation only persists for lower NADW. Upper and mid-depth layers of the deep limb (Labrador Sea Water and NADW), in contrast, experience recirculation in the subpolar and subtropical gyres. The boundary between the gyres, also known as the Western Transition Zone, governs export to the subtropics based on convergence within the deep subpolar gyre.

The upper and lower limbs are more closely linked in the subpolar gyre because this is a key region of water mass transformation. There are many recent results that precede the initial reports from the OSNAP array. In the Labrador Sea, Holte and Straneo (2017) used ARGO profiles to show that deep water formation varies seasonally by factors of 2 to 3 and is strongest in density space, suggesting that a continuous record of seasonality is needed to accurately capture interannual signals. In addition to surface buoyancy forcing, the ocean preconditions convection sites by advecting density anomalies from boundary currents by eddy fluxes. Eddy fluxes induce a 5–10 year lag in response to freshwater runoff (Manucharyan et al. 2017). More generally, this lag provides an “eddy memory” that requires improved parameterizations in non-eddy resolving models (Manucharyan et al. 2017). Boundary currents also transport dense water to the sills that feed the deepest overflow waters in the North Atlantic (Almansi et al. 2017). Overflow waters are influenced in part by runoff around Greenland (Havik et al. 2017), by wind-stress (Bringedahl et al. 2017), and by topographically constrained jets (Pickart et al. 2017).

An additional commonality of the above studies is that convergence within gyres drives potentially extra-gyre impacts. This applies to mass transport in the deep limb (Buckley and Lozier), boundary current position (Kelly and Thompson), and heat storage or sea level (Kelly and Thompson).
2.2.2 What AMOC fingerprints are found in multiple studies that provide consensus on current and past AMOC states?

Synthesis of observations and models requires finding robust patterns independent of model or methodological approach. Similar to the efforts described above to identify low-frequency and large-scale patterns from observations, the multiplicity of high-variance, high-frequency, and small-scale signals are not expected to be similar between coupled models or ocean reanalyses, so the question becomes extracting robust patterns. Examples of this include the SST pattern of AMV that is seen across studies as well as the coherence within gyres.

Considering a suite of CMIP5 models, Srivastava and DelSole (2017) applied a new statistical approach, Laplacian eigenvectors, to identify common modes between AMOC and SSH. They found that only the single lowest eigenvector is robust across models — small-scale structure is model dependent. Though SST in coupled models doesn't require an interactive AMOC, ocean dynamics define the duration of predictability (Srivastava and DelSole 2017). A second predictor, lagged by 5-years, increases skill, however, and is related to the impact of ocean advection. They plan to extend their results to create an AMOC reconstruction based on observational SST reanalyses.

Consideration of ocean reanalyses, models, and observations in the South Atlantic (Perez, Matano, and Garzoli) shows that interannual to decadal scales are governed by gyre spin up and spin down. Ocean reanalyses show gyre strength is related to SAMOC strength, MHT, and SST in the entire Atlantic basin. A strong influence is found from ENSO but with a range of influence restricted to within 30° of the equator. The connection between these signals and their relationship with other basins are ongoing efforts.

2.3 Assessment of AMOC variability and mechanisms

The primary theme of Task Team 3 projects is to model and understand AMOC dynamics, mean state, and variability. The projects in Task Team 3 can be categorized into three broad themes: i) understanding the mean state of AMOC; ii) role of AMOC in low frequency climate variability (in the atmosphere and ocean); and iii) high-resolution representations of key AMOC components.

2.3.1 Understanding the AMOC mean state

- “Evaluation and Diagnosis of the Atlantic Meridional Overturning Circulation 3D Structure in Climate Models” (Xu, Chassignet, Baringer, and Dong)
- “Dynamics of Cross-Equatorial Flow” (Spall and Nieves)
- “Amplified North Atlantic Warming in the Late Pliocene by Changes in Arctic Gateways (Otto-Bliesner, Jahn, Feng, Brady, Hu, Lovferstrom)
- “Collaborative Research: Understanding the Freshwater Budget of the Atlantic Ocean: Controls, Responses, and the Role of the AMOC” (Cheng, Danabasoglu, Yeager, Weijer, Chiang, D. Zhang, Kim, Gent, J. Zhang)

Understanding the mean state of the AMOC remains an active area of research. Xu et al. (2017) diagnosed the water mass transformation in density space in a high-resolution model of the North
Atlantic. They decomposed the transformation into interior and mixed layer regions, and noted
the importance of the zonal structure of the mixing that is often obscured by zonal averaging
in traditional calculations of AMOC. The role of the equator, and Kelvin and Rossby waves, in
setting up the mean stratification at mid-depths is being explored in idealized numerical models
and theory by Spall and Nieves. It has been found that the thickness of NADW throughout the
Atlantic Basin, in the limit of weak diapycnal mixing, is controlled by the latitude of the southern
tip of Africa and the formation rate of NADW, and that variability in the meridional transport
of NADW anomalies strongly decreases away from the source region, even in the absence of
mixing. Otto-Bliesner et al. (2016) found that the closure of the Bering Strait and/or the Canadian
Arctic Archipelago results in reduced freshwater transport into the subpolar North Atlantic, a
strengthened AMOC, and higher SST, which may explain a cold bias found in models of the late
Pliocene. Cheng and colleagues studied the salt feedback on AMOC in Earth system models
by employing the Fov diagnosis. They found that the link from AMOC to Fov occurs via two
mechanisms: change in meridional velocity vertical structure and change in the salinity vertical
profiles, with the latter being dominant.

2.3.2 Role of AMOC in low-frequency climate variability

- “Identifying Mechanisms of AMOC Variability in ECCO State Estimates and CMIP5 Models”
  (Buckley, Heimbach, and Ponte)
- “Understanding Changes in the Atlantic Meridional Overturning Circulation (AMOC) During
  the 20th Century Using IPCC AR5 Model Ensembles” (Chang, Danabasoglu, and Yeager)
- “Variability, Stochastic Dynamics, and Compensating Model Errors of the Atlantic Meridional
  Overturning Circulation in Coupled IPCC Models (Penland, MacMartin, and Tziperman)
- “The Role of Ocean Dynamical Feedback and Air-Sea Interaction in the Climate Response to
  Global Warming” (Liu and Xie)
- “The Southward Returning Pathways of AMOC and Their Impacts on Global Sea Surface
  Temperature” (Lee and Goes)
- “On the Persistence and Coherence of Subsurface Temperature and Salinity Anomalies
  Associated with the Atlantic Multidecadal Variability (Zhang)
- “Fate of the Atlantic Meridional Overturning Circulation: Strong Decline Under Continued
  Warming and Greenland Melting” (Schmittner and Hu)
- “Internally Generated and Externally Forced Multidecadal Oceanic Modes and Their
  Influence on the Summer Rainfall over East Asia” (Si and Hu)
- “A Collaborative Multi-Model Study: Understanding AMOC Variability Mechanisms and Their
  Impacts on Decadal Prediction” (Danabasoglu, Yeager, Karspeck, Tribbia, Delworth, Msadek,
  Rosati, Kwon, Frankignoul)
- “Collaborative Research EasM2: Mechanisms, Predictability, Prediction, and Regional
  and Societal Impacts of Decadal Climate Variability” (Danabasoglu, Anderson, Branstator,
  Lindsay, Tribbia, Frankignoul, Kwon, Zhang)

The majority of projects under Task Team 3 relate broadly to the role of AMOC in low-frequency
climate variability as represented by global temperatures, air-sea exchange, and oceanic heat
storage. The primary tool in these studies is analysis of ensembles of coupled climate models of
relatively low resolution and long simulation times. Buckley and colleagues use the ECCO state
estimate and several CMIP5 models to demonstrate that i) the recent cooling trend in the subpolar North Atlantic is due to changes in wind-driven transport from low latitudes (Piecuch et al. 2017); ii) local wind dominates AMOC at 34°S for subannual timescales but remote forcing becomes more important at longer timescales; and iii) upper ocean heat content predictability is longest in the North Atlantic subpolar gyre and may be coupled to wintertime mixed layer depth. Kim et al. (2018) used coupled CESM Large Ensemble runs and ocean hindcast simulations to diagnose AMOC changes in the 20th century. They found generally weaker variability in the coupled runs compared to the forced hindcast runs, which they attributed to a too-weak North Atlantic Oscillation (NAO) signal in the atmosphere of the coupled models. Penland, MacMartin, and Tziperman used two coupled IPCC models, subject to preindustrial and four times CO$_2$ forcing, and found a shift in the location and amplitude of spectral peaks in AMOC and heat transport, which was due to a shift in the controlling ocean circulation (MacMartin et al. 2016). They also applied a linear inverse modeling technique to evaluate how much of AMOC variability is deterministic versus stochastic. The two models yielded different results, perhaps related to the relative importance of temperature and salinity in controlling density variability (Zhao et al. 2017).

Biases in freshwater transport common to coupled climate models place them in a more stable AMOC state compared to observational estimates of salt transport into the Atlantic basins. Liu et al. (2017) found that artificially correcting for this bias resulted in a collapsed AMOC under double CO$_2$ forcing with corresponding large changes in sea ice extent, atmospheric temperatures, and position of the ITCZ. CESM Large Ensemble simulations were used to infer that the recent slowdown in global warming was due to increased heat storage in the upper Indian Ocean in response to increasing Pacific trade winds (Liu et al. 2016). Using the CESM Large Ensemble, Si and Hu (2017) found that the Interdecadal Pacific Oscillation is due to inherent ocean variability while the AMV may be generated internally (by AMOC) but modulated by atmospheric forcing in the 20th century. Lee et al. (2017) related a poleward shift in the Southern Ocean westerlies to a strengthened Weddell Gyre, increased blocking of poleward heat transport, and seaward expansion of sea ice. Murphy et al. (2017) find that dust-climate feedbacks may provide an amplification of Heinrich cooling events by weakening AMOC and increasing North Atlantic sea ice coverage. Zhang (2017) used observations and a fully coupled climate model to argue that ocean forcing plays a dominant role in the subpolar North Atlantic SST anomalies associated with the AMV. This is in contrast to studies with a slab ocean model that also reproduce features of the AMV (Clement at al. 2015).

Several recent studies by Danabasoglu and colleagues address the relationship between the AMV and important components of the climate system. Ensemble calculations using three different coupled climate models looked at the influences of imposed AMV SST anomalies on heat waves and climate extremes (Ruprich-Robert et al. 2018), Arctic sea ice (Castruccio et al. 2018), and atmospheric blocking patterns. Early work has also begun on the influences of Labrador Sea water formation on low-frequency variability of MHT and SST. In a separate project, Danabasoglu and colleagues are working to produce a decadal prediction system for both climate and the marine ecosystem, with biogeochemical components, and to consider regional and societal impacts. The decadal prediction system has demonstrated the importance of initializing with AMOC related heat anomalies in the improvement predictions of summertime Sahel precipitation and components of the ocean biosphere (Yeager et al. 2018). Another recent study by Frankignoul
et al. (2018) used two large ensembles to compare how well various statistical methods are able to estimate SST changes due to both external and anthropogenic forcing. Optimal patterns of external forcing AMOC anomalies, identified using the fluctuation dissipation theorem (FDT), have been found to produce not only strong AMOC but also to continue to grow after the anomalous forcing ceased. Based on analysis of winter weather patterns between 2013 and 2016, Xie and Zhang (2017) suggest that some SST anomalies lead to more predictability of extreme climate events and that probabilistic extreme climate prediction is necessary since low-probability events may occur, such as in the winter of 2014/15.

2.3.3 High resolution representation of AMOC

- “Subpolar-Subtropical Connectivity of the North Atlantic Circulation” (Xu and Chassignet)
- “Mechanisms of Freshwater Exchange Across the East Greenland Shelf” (Spall and Haine)
- “The Interannual Variability of the Brazil Current” (Goes, Lee, Dong)
- “Understanding Drivers and Impacts of CGCM Biases in Representing the Decadal Variability in Labrador Sea Convection” (Bracco, Ito, Tagkalis)
- “Interannual to Decadal Variability in the South Atlantic MOC” (Dong and Lee)

A growing number of projects are devoted to using high-resolution models and theory to understand key regions or processes related to AMOC. Tagklis et al. (2017) evaluated the oxygen uptake in numerous CMIP5 models, finding they can reproduce observations during the period 1975–2005. They generally project increasing temperatures and decreasing solubility, decreased nutrient supply to the upper ocean, and decreasing oxygen over the next century. They are also developing a regional, high-resolution model of the Labrador Sea for the evaluation of meso- and sub-mesoscale physics in deep convection and primary productivity. A regional, high-resolution model of the Denmark Strait region has been developed by Haine and colleagues. Several two year-long simulations have been used to describe the variability in Denmark Strait and explore the role of mesoscale variability in the transport over the sill (Alamasi et al. 2017). Idealized models, theory, and observations were used to estimate the amount of low salinity advected water out of fjords and across the shelfbreak, where it may reduce deep convection, by katabatic winds (Spall et al. 2017; Spall and Pedlosky 2017). These wind events represent an important, although not dominant, component of the salinity budget both in the fjords and shelf of east Greenland. Chassignet and Xu (2017) evaluated the Gulf Stream and North Atlantic current mean path and eddy kinetic energy as a function of increasing resolution, from 1/12° to 1/50°, and found realistic separation, variability, and vertical structure at the highest resolution. Low- and high-resolution coupled ocean-atmosphere models of the Brazil Confluence were used by Siqueira et al. (2017) to demonstrate the regional influences of mesoscale currents on rainfall, air-sea fluxes, and SST, with the eddy resolving model in better agreement with observations. A similar approach of combining low-resolution climate models and eddy-resolving models is being used by Dong and Lee to explore the role of mesoscale eddies in meridional heat flux and low-frequency variability in the South Atlantic MOC.

2.4 Climate sensitivity to AMOC: Climate and ecosystems impact

Task Team 4 seeks to better understand the relationship between changes in the AMOC and other components of the Earth system with an emphasis on: i) SST, ii) ocean heat content and
sea level, iii) atmospheric circulation patterns and the hydrological cycle, iv) the cryosphere, and v) biogeochemical cycles and marine ecosystems. Ten current projects involve these themes. The results from these projects, as well as those presented at the US AMOC meeting, are summarized below.

2.4.1 Origin of Atlantic SST variability (the AMV)

The 2017 US AMOC meeting included a special session highlighting recent investigations of the relationship between the AMOC and low-frequency variability of North Atlantic SST, the AMV. Projects related to this topic and presentations in the special session include:

- “Decadal Variability of Interacting Climate Subsystems in the Northern Hemisphere” (Kravtsov, Tsonis)

In a recent paper, Clement et al. (2015) demonstrate the feasibility of basin-wide warming on multidecadal timescales (e.g., the AMV) due to atmospheric forcing alone. They find that slab-ocean models simulate the same AMV pattern as the observations and corresponding simulations with most fully coupled models. Several subsequent studies (O’Reilly et al. 2016; Peings et al. 2016; Zhang et al. 2016) argue that slab-ocean models cannot explain the AMV because they cannot match the observed correlations between SST and air-sea heat fluxes on multidecadal timescales (warm SST corresponding to flux out of the ocean). Cane et al. (2017) use a simple model to show that the observed correlations between SST and air-sea heat fluxes occur as a result of low-pass filtering and occur even when the ocean contribution to the heat budget is small. However, Zhang (2017) argues that Cane’s model is incomplete because it omits oceanic damping.

The AMV has typically been considered an internal atmosphere-ocean mode of variability, but recent work demonstrates that external radiative forcing, particularly aerosol forcing, can drive multidecadal SST variability (Bellucci et al. 2017; Murphy et al. 2017; Bellomo et al. 2017). Bellomo et al. (2017) show that the ensemble mean of the AMV index in the CESM Large Ensemble (LE) and Large Millennial Ensemble is strongly correlated with the observed AMV index, suggesting that the timing of the AMV is primarily set by external forcing.

Using the CESM LE, Maroon and collaborators show that an increase in AMOC strength relative to the ensemble mean is associated with amplified global surface warming. This surface warming accounts for roughly 30% of the variance in historical period surface warming trends and specifically occurs in the Nordic and Barents seas and over northern Eurasia.

One caveat of studies that use models to understand the origin of the AMV is that coupled models often have weaker multidecadal SST variability than observed. Kravstov and collaborators use model simulations to isolate forced and internal components of variability in models and observations. They find important differences between the observed and simulated interannual-to-decadal climate variations.
2.4.2 Relationship between AMOC, ocean heat content, and sea level

One project and two presentations at the US AMOC meeting focused on the relationship between the ocean circulation and Atlantic Ocean heat content:

- “Identifying Mechanisms of AMOC Variability in ECCO State Estimates and CMIP5 Models” (Buckley, Ponte, Heimbach)

Piecuch et al. (2017) use the ECCO state estimate to show that the subpolar North Atlantic ocean heat content trend reversal from 1994–2004 to 2005–2015 arose largely from variable heat transports by the ocean's mid-latitude horizontal gyre circulation that are strongly correlated with the local wind field.

Buckley and collaborators diagnose predictability timescales of upper ocean heat content from i) ocean data products and ii) control runs of CMIP5 models. They find that predictability timescales of upper ocean heat content are related to the climatological wintertime mixed-layer depth.

The projects and presentations related to the interaction between the ocean circulation and sea level are as follows:

- “Signature of the Atlantic Meridional Overturning Circulation in the North Atlantic Dynamic Sea Level” (Yin, Griffies, and Zhang)

Little et al. (2017) use the CESM LE understand past and future coastal sea level changes along the northeastern US coast; they conclude that observation-based interpretations, highlighting the role of winds, are compatible with a dominance of AMOC-associated changes in the 21st century. Furthermore, the study suggests the time periods over which coastal sea level may be used as a proxy for the large-scale ocean circulation.

J. Yin and collaborators investigate the linkage between a 30% downturn of the AMOC during 2009–10 and an extreme sea level rise event along the northeast coast of North America (Goddard et al. 2015; Goddard 2017). They find that in addition to the North Atlantic Oscillation, the slowdown of the AMOC during 2009–2010 was also an important factor in causing the pronounced coastal sea level spike in 2010 north of New York City.

2.4.3 Relationship between changes in the AMOC and/or AMV and atmospheric circulation patterns and the hydrological cycle

- “Impact of the Atlantic meridional overturning circulation on multidecadal variability of Atlantic major hurricane frequency” (Zhang)

- “Inter-hemispheric variability of the South and North Atlantic MOCs and its decadal modulations of global monsoon circulations and extreme weather events in the US” (Lopez, Dong, and Lee)

Using observations and a coupled earth system model (GFDL-ESM2G), Zhang et al (2017) show that the decline of the Atlantic major hurricane frequency since 2005 is associated with a weakening of the AMOC inferred from ocean observations.
Lopez and collaborators study the impact of the AMOC on climate variability and extreme weather events over the United States on decadal timescales. They find that external forcing dominates heat wave occurrence over some regions, whereas internal variability dominates over other regions, suggesting a potential role for changes in the Atlantic Ocean circulation.

### 2.4.4 Interactions between the cryosphere and the ocean circulation

There were several projects related to the interaction between the AMOC and the cryosphere, including both ice sheets and sea-ice.

- “Modeling Effects of Ice Sheet Changes on AMOC Variability” (Schmittner, Hu, and Mernild)
- “Understanding mechanisms of projected 21st century ocean warming around Greenland” (Little and Yin)
- “Comparison of Mechanisms for Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models” (Zhang)
- “On the Discrepancy between Observed and CMIP5 Multi-Model Simulated Barents Sea Winter Sea Ice Decline” (Zhang)

Schmittner and collaborators have organized an international model intercomparison project (AMOCMIP) that focuses on including Greenland Ice Sheet melting in future projections. AMOCMIP results show that Greenland Ice Sheet melting leads to a significant additional AMOC reduction in some models but not in others. Bakker and Schmittner (2016) develop an AMOC emulator fitted to the AMOCMIP results in order to perform probabilistic AMOC projections. These results support the finding that GIS melting can decrease the AMOC further; although its effect is smaller than that of warming and changes in the hydrological cycle (Bakker et al. 2016a).

Schmittner and collaborators also investigate the effects of Antarctic Ice Sheet variations on global and regional climate variability and the AMOC. They find that freshwater fluxes due to melting of the Antarctic Ice Sheet lead to variability of surface and subsurface temperatures and the AMOC, and a positive feedback between Antarctic Ice Sheet and surface warming is proposed (Bakker et al. 2016b).

Zhang and collaborators use models and observations to investigate the impact of Atlantic low-frequency variability on the observed decline of (i) summer Arctic sea ice extent and (ii) Barents Sea winter sea ice extent. They find that models enhanced by Atlantic heat transport into the Arctic induces summer Arctic sea ice decline and surface warming, especially over the Atlantic sector of the Arctic (Li et al. 2017). They find that the observed decline of wintertime Barents Sea ice concentration since 1979 cannot be explained by external forcing. In contrast, sea ice concentration trends are strongly anti-correlated with trends in Atlantic heat transport across the Barents Sea opening, suggesting a controlling role by the ocean.

### 2.4.5 Impact of biogeochemical cycles

The following studies were presented at the 2017 US AMOC Science Meeting. The investigators on these projects are being invited to join the US AMOC Science Team.
Gnanadesikan and collaborators examine the link between the AMV and biological variability in the North Atlantic using two Earth systems models and data from the continuous plankton recorder. Changes in productivity are related to changes in convection and the AMV, but the biological response is heterogeneous with different impacts in different regions and for different functional groups. These results suggest that a simple “regime shift” picture is not appropriate for the whole Atlantic.

Tagklis and collaborators study the response of oxygen concentrations to climate change using CMIP5 models. They find that there is decrease in the strength of the North Atlantic Current, leading to i) a warming hole and thermodynamically driven decreases in oxygen concentrations over the North Atlantic and ii) a reduction of nutrients injected into the mixed layer, leading to lower biologically driven oxygen utilization.

Chi, Gnanadesikan, and collaborators examine whether transient tracers concentrations (e.g., oxygen, CFC) can be used as proxies for the AMOC at different latitudes in the North Atlantic.
The near- and long-term research priorities, articulated below, are based on the discussions that occurred during previous US AMOC Science Team meetings and teleconferences. Long-term priorities are meant to be forward-looking scientific questions that will require research beyond the sunset of the Science Team, which may also be true for some of the near-term priorities as well.

3.1 Observing system implementation and evaluation

In situ observations are essential for improved understanding of the causes and consequences of variability in the AMOC. Since a variety of processes, operating on multiple spatial and temporal scales, contribute to the AMOC, observations are aimed at providing a measure of the full-depth, basin-wide AMOC volume, heat, and freshwater transports throughout the Atlantic Ocean from the southern limit at 34.5°S to the northern limits where Atlantic-Arctic exchanges occur. The goal is to implement and sustain an observing system at sufficient spatial (zonal and meridional) and temporal resolution to both monitor changes and to elucidate the underlying processes. In situ observations are also critical for characterizing the AMOC for model assimilation and validation.

3.1.1 Near-term priorities

- Improve understanding of the meridional coherence (and/or lack thereof) of the AMOC and the mechanisms that control AMOC variability. Characterize and investigate coherence within the subpolar and subtropical gyres, communication between the gyres, and communication of changes across the equator to the South Atlantic.
- Develop dynamically consistent model-data synthesis methods to combine the heterogeneous observational components.
- Seek new potential funding mechanisms to sustain key elements of the US AMOC observational networks.
- Better characterize the deep ocean to quantify the role of deep temperature and salinity signals that contribute to AMOC variability through enhancements to the observing system that directly measure deep ocean properties (temperature, salinity, and velocity) such as Deep Argo, Deep gliders, and moored instrumentation.
- Ensure that AMOC estimates are made available in widely recognized locations, such as the World Ocean Database, OceanSITES, the National Center for Environmental Information (NCEI), etc. AMOC estimates should be accompanied by their key underlying measurements as well as their error estimates on multiple timescales from weeks to months to years. This allows the necessary information for analyses, inter-array comparisons, and numerical model studies.
• Improve communication within the US AMOC observing system groups and between national and international programs.

3.1.2 Long-term priorities

• Develop new sustainable technologies and methods to achieve the overall observing system goal to characterize AMOC. This includes novel combinations of in situ and remotely sensed data with modeling efforts. These activities will need to be mindful of constraints due to limited financial resources.
• Observe and study the shallow and deep AMOC pathways. Existing in situ trans-basin arrays will remain sparsely separated and measurements are required to reveal these pathways. This may involve targeted Lagrangian studies in the South Atlantic and/or tropical Atlantic regions, in situ arrays at key transition regions, and will surely require the development of new technologies and/or techniques.
• Assist in rigorous testing of data assimilation schemes. Identify observations that improve AMOC representation and identify gaps in the current observing systems. This will require continued communication between the US AMOC community and the data assimilation community and will benefit from the proposed focus on developing common AMOC metrics.

3.2 Evaluation of AMOC state, variability, and change

The focus of Task Team 2 is to identify common patterns and mechanisms to explain the present AMOC circulation state, its variability, and long-term change. Progress comes from finding similarities between multiple observational and modeling studies. Therefore, this Task Team synthesizes results from multiple methodological approaches, with a goal to identify consistent and inconsistent AMOC signals. This effort shares significant overlap with Task Teams 1 and 3, as well as with the new Task Team on Paleo AMOC. Consistent signals from observations and models are generally found within gyres or in their surface expression (as described in section 2.2). Non-robust signals, however, provide focus for further research.

3.2.1 Near-term priorities

Our discussion identified thematically organized questions on which immediate progress can be made based on lack of consensus between different approaches.

AMOC Characteristics
• Depth extent of AMOC cells
• Level of high-frequency variability
• Dominant timescales of variability
• Long-term trends of overturning strength

Coherence between gyres
• Role of planetary waves varies between models in terms of patterns, timing, and forcing
• Balance between high-latitude wind versus buoyancy forcing (observations or models)
• Subtropical/Southern Ocean connectivity, including geostrophic reference level
• Nature of coherence in the upper AMOC branch, as related to observational coverage (well-resolved temperature and upper ocean circulation versus poorly sampled salinity and deep ocean)
• Impact of eddies and indirect (and unknown) water parcel pathways, and their resulting transfer between gyres.
• Relation between Eulerian and Lagrangian perspectives of coherence

Methodological improvements for comparison and synthesis
• Consistent metrics to compare models and observations, including observational methods and assumptions, and whether calculated in depth or density space
• Quantifying uncertainty in data products
• More explicit synthesis of Eulerian and Lagrangian descriptions of overturning, especially as influencing advective fluxes of climatically relevant quantities (heat, freshwater, carbon, etc.)

One barrier to productive comparisons is that different assumptions or approaches are used for different observations, or between observations and models. More careful comparisons will hopefully provide clearer results and, in the case of model-observation comparisons, will suggest model improvements for parameterizations of overflows, deep convection, and mixing.

More generally, we are most interested in transport of quantities that interact with the atmosphere and influence the climate, such as heat, freshwater, momentum, carbon, or nutrients. Advective fluxes have different dynamics than the mass transport and its kinematics that define the AMOC. Flow pathways and mixing are Lagrangian, whereas overturning strength or latitudinal coherence are implicitly Eulerian. Throughput of the AMOC, and connection between gyres where dynamical balances differ, requires understanding from each framework. With overturning arrays now in multiple basins and growing time series from each, we anticipate progress in understanding coherence, gyre connectivity, and ultimately control on advective fluxes.

3.2.2 Long-term priorities

• Use new and existing observations in combination with modeling experiments to refine our understanding of the present and historical circulation (and related transports of heat and freshwater as well as flow pathways) in the North and South Atlantic.
• Focus on mechanisms and pathways that identify and explain coherent and incoherent signals between different study sites, thereby reaching consensus on which signals represent the large-scale AMOC versus more localized circulation patterns.
• Synthesize modeling and observational evidence to build scientific consensus on the variability and change of the AMOC over the last 50 years, using and defining observable proxies as appropriate.
• Focus on reaching a consensus on the evolution of the AMOC over the last 50 years, using the data assimilation community, and consistent with other lines of observational evidence.
3.3 AMOC mechanisms and predictability

Task Team 3 seeks to identify key physical processes at work in the maintenance and modulation of the AMOC in past, present, and future, and to apply this understanding to predictions of AMOC-related climate variability. Approaches include the use of comprehensive coupled climate models; regional, high-resolution models; idealized or process models; theory; and in situ and remotely sensed observations. The working hypothesis is that there are robust and potentially predictable driving mechanisms at work on timescales ranging from intraseasonal-to-millennial that can be anticipated from theory, studied in isolation using appropriate idealized models, and identified as active and important in more comprehensive GCMs of ever-increasing complexity. Success is to be measured by the identification of mechanisms of AMOC variability that are well understood across the spectrum of available tools and facilitate the interpretation of past, and the reliable anticipation of future, climate change related to AMOC.

3.3.1 Near-term priorities

- Investigate how surface exchanges of buoyancy and momentum between the ocean and the atmosphere/cryosphere drive the AMOC circulation across a broad range of timescales from monthly to millennial (i.e., quasi steady-state).
- Clarify the apparent disagreement between models of different complexity regarding: i) the role of Southern Ocean wind and ii) the role of Nordic Seas overflows in maintaining and modulating the AMOC.
- Quantify the magnitude, location, and physical mechanisms associated with interior diapycnal mixing in the ocean, which contribute to the diabatic AMOC, and evaluate the realism of current GCMs in this regard.
- Investigate the role of freshwater forcing and South Atlantic freshwater transports in determining the variability and stability of the AMOC.
- Expand the use of eddy-resolving models, particularly in regional/process studies designed to: i) test the robustness of AMOC variability mechanisms identified in coarser GCMs or idealized models; ii) address the origins of persistent model bias in the North Atlantic region (e.g., Gulf Stream separation and the North Atlantic Current path); and iii) assess the role of ocean turbulence in AMOC variability.
- Quantify the predictability properties of AMOC in idealized and comprehensive models and identify mechanisms that affect these properties.
- Explore the mechanisms associated with AMOC variability on centennial-to-millennial timescales, and evaluate the realism of GCMs on these timescales relative to available paleo proxy data, perhaps using proxy-enabled coupled climate models.

Much of the Task Team 3 activities over the past year is directly related to this list of near-term priorities (see Section 2), which reflects input from the Science Team, telecons, and the 2017 annual meeting. This list resembles prior near-term priority lists because i) they remain relevant and ii) these are major, comprehensive issues that defy simple closure.

Task Team 3 is continuing the successful webinar series from 2016–17 to the 2017–18 academic year. While the prior series was organized around the influences of freshwater on AMOC, this
year the subject area was broadened to the overarching TT3 topic area of mechanisms of AMOC variability and predictability. Webinars take place once per month, and archived recordings are available. The response in terms of volunteer presenters and audience participation has been very strong.

3.3.2 Long-term priorities

Task Team 3 long-term priorities emphasize outstanding science questions and strategic goals, which will require more time and more complex and resource-intensive models to fully explore and realize, as well as the ongoing synthesis efforts that attempt to build consensus knowledge about AMOC variability from the many disparate results coming out of Task Team 3. These long-term priorities are:

- Translate the knowledge developed about AMOC variability and predictability mechanisms into reliable decadal climate forecasts.
- Incorporate mesoscale eddy-resolving ocean models more fully into the toolkit used for AMOC mechanisms/prediction studies, including long coupled GCM simulations, in order to address questions about the role of turbulence in controlling AMOC.
- Synthesize results from theoretical, idealized models, and more complex GCM investigations into a common conceptual framework regarding key AMOC variability mechanisms and identify the resulting predictability of the AMOC.

Significant progress is being made on the development of mesoscale eddy-resolving models in both regional and basin-scale applications, as summarized in Section 2.3.3. Ensemble models of moderate resolution are being used to develop consensus low-frequency variability mechanisms, but linking these to theories and idealized models has not really started. Relating knowledge of mechanisms to reliable decadal climate forecasts remains the overarching long-term goal of Task Team 3.

3.4 AMOC Impacts

The focus of Task Team 4 is the relationship between the AMOC and other components of the climate system. While Task Team 4 has traditionally been focused on AMOC impacts, our improved understanding of the two-way nature of the climate system, as well as vigorous debate regarding causality (e.g., the origin of the AMV), lead us to recast our priorities in terms of interactions between various components of the climate system and the AMOC. For example, we seek to understand interactions between the AMOC and SST, global and regional sea level, and the cryosphere, rather than just the impact of the AMOC on these components of the climate system.

During the 2017 meeting, we discussed our near-term priorities in detail and found some of them to be too general. We sought to focus on specific interactions between the AMOC and other components of the climate system that are well-documented, but our understanding of them is incomplete and, thus, ripe for research. In addition to existing priorities (e.g., sea level, cryosphere, biogeochemistry), additional topics were highlighted:
1. The impact of the AMOC on the Inter-Tropical Convergence Zone (ITCZ).
2. The interaction between the AMOC and the hydrological cycle, including clouds.
3. The relationship between the AMOC and climate extremes, including hurricanes, droughts, and flooding events.

We also modified our long-term priorities to include the teleconnections of AMOC variability with variability in other ocean basins (e.g., Southern Ocean). Additionally, we would like to engage the paleoclimate community in order to understand the impacts of the AMOC on centennial and longer timescales.

### 3.4.1 Near-term priorities and key questions

**Relationship between AMOC, the ITCZ, and the hydrological cycle**

Modeling experiments seem to clearly suggest an impact between imposed changes in the AMOC and shifts in the ITCZ. However, ITCZ shifts in coupled models appear to be damped in contrast to slab models. The impact of internal variability of the AMOC on the ITCZ is more uncertain, but there are interesting recent results, including high predictability of shifts in the ITCZ position (Martin and Thorncroft 2015), which seem to be related to changes in the AMOC in the subpolar North Atlantic. However, several key questions remain unaddressed, including:

- What is the impact of model biases on the ability to capture AMOC variability and teleconnections?
- What are the interactions between the AMOC, AMV, and changes in different types of clouds?

**Relationship between the AMOC and global and regional sea level**

- Does the AMOC and resulting ocean heat transport have a significant impact on regional sea level? How does it compare to other factors (e.g., local winds, changes in the Gulf Stream path)?
- Can sea level be used as a proxy for the AMOC?

**Relationship between the AMOC and the cryosphere**

- What are the mechanisms for warming along the ice shelf in Greenland? Related to the AMOC? Local winds?
- What is the impact of the melting of the Greenland Ice Sheet on the AMOC (e.g., Oceans Melting Greenland project)?

**Relationship between the AMOC and climate extremes**

- What is the impact of the AMOC on hurricanes?
- What is the impact of the AMOC on droughts?
- How can the CMIP6 decadal MIPs be used to understand AMOC variability and related climate impacts?

**Relationship between the AMOC, the carbon cycle, and marine ecosystems**

- How does the AMOC impact the carbon cycle?
- What is the impact of the AMOC/AMV on fisheries?
3.4.2 Long-term priorities

The long-term goal of Task Team 4 is to understand how AMOC variability interacts with other components of the Earth system — its climate, hydrologic cycle, atmospheric circulation, coupled phenomena (e.g., ENSO, monsoons), other ocean basins (e.g., Southern Ocean), cryosphere, sea level, marine and terrestrial ecosystems, biogeochemical cycles, and carbon budgets. As discussed at the 2017 meeting, we would like to engage the paleoclimate community in order to understand the impacts of the AMOC on centennial and longer timescales.
Summary of Long-Term Priorities

**Task Team 1**

Develop new sustainable technologies and methods to achieve the overall observing system goal to characterize AMOC. This includes novel combinations of *in situ* and remotely sensed data with modeling efforts.

Observe and study the shallow and deep AMOC pathways.

Assist in rigorous testing of data assimilation schemes. Identify observations that improve AMOC representation and identify gaps in the current observing systems.

**Task Team 2**

Use new and existing observations in combination with modeling experiments to refine our understanding of the present and historical circulation (and related transports of heat and freshwater as well as flow pathways) in the North and South Atlantic.

Focus on mechanisms and pathways that identify and explain coherent and incoherent signals between different study sites, thereby reaching consensus on which signals represent the large-scale AMOC versus more localized circulation patterns.

Synthesize modeling and observational evidence to build scientific consensus on the variability and change of the AMOC over the last 50 years, using and defining observable proxies as appropriate.

Focus on reaching a consensus on the evolution of the AMOC over the last 50 years, using the data assimilation community, and consistent with other lines of observational evidence.

**Task Team 3**

Translate the knowledge developed about AMOC variability and predictability mechanisms into reliable decadal climate forecasts.

Incorporate mesoscale eddy-resolving ocean models more fully into the toolkit used for AMOC mechanisms/prediction studies, including long coupled GCM simulations, in order to address questions about the role of turbulence in controlling AMOC.

Synthesize results from theoretical, idealized models, and more complex GCM investigations into a common conceptual framework regarding key AMOC variability mechanisms and identify the resulting predictability of the AMOC.

**Task Team 4**

Understand how AMOC variability interacts with other components of the Earth system — its climate, hydrologic cycle, atmospheric circulation, coupled phenomena (e.g., ENSO, monsoons), other ocean basins (e.g., Southern Ocean), cryosphere, sea level, marine and terrestrial ecosystems, biogeochemical cycles, and carbon budgets.
This section is complementary to the US AMOC program research priorities discussed above, which are also available on the program website. It is very similar in content to the previous reports, summarizing activities to achieve both near- and long-term priorities.

### 4.1 Large-scale observations

The US AMOC observational research projects, coupled with other existing large-scale sustained observing systems (e.g., Argo, satellite measurements, repeated CTD and XBT ship sections, surface drifters) are critical for improving understanding of the AMOC and the large-scale climate system, as are synthesis efforts to combine the data streams into a coherent dynamical framework for models studies. The general requirements for sustained large-scale observations and synthesis were described in detail in the 2010 US AMOC Science Team report and are not repeated here. They have remained, and will remain for the foreseeable future, the same. Recent research continues to demonstrate the urgent need to maintain global-scale, continuous observing systems in order to understand climate variability on decadal and longer timescales, including the AMOC observing projects. These programs are based on the detailed requirements for the sustained ocean observing system that were established at the Ocean Obs’09 Conference. The responsibility for the design and implementation of these observing systems relies on NASA, NOAA, NSF, and the many national and international partner agencies around the world, and will require resources above and beyond those that can be explicitly provided by the US AMOC program to be successful. As such, it is imperative that all available US resources continue to maintain the observing systems while at the same time working to enhance and improve our international relationships in order to best utilize the capabilities of many nations.

### 4.2 Proxy records and analysis

Decades of paleo research have shown a clear link between cold harsh epochs and reduced AMOC on orbital to centennial timescales. An assessment of whether this relationship exists on interdecadal timescales continues to be of central importance to the US AMOC program goals. The establishment of the Paleo AMOC Task Team is expected to enable cross-disciplinary collaborations between the paleo and modern oceanographic communities.

Regarding fingerprints of AMOC variability on multidecadal and centennial scales, the following activities should be considered by the new Paleo AMOC Task Team:

- Spatial coverage and temporal resolution of paleo-climate data need to be expanded and improved. There are probably fewer than a dozen deep ocean records in the North Atlantic that are suitable to resolve changes on decades to centuries. This is in contrast with
hundreds to thousands of sites on land around the North Atlantic basin. To resolve decadal changes requires sampling at the centimeter scale (very expensive) and dating very closely.

• Sufficient, well-resolved sites are needed to determine if the observed paleo changes reflect truly low-frequency variability on multidecadal and centennial scales.
• Multiproxy studies are needed. No single paleo proxy measurement is sufficient to recreate ocean circulation changes. Combinations of measurements on the same samples are required for robustness.
• Analyses of AMOC state and variability should explore the relationship between potential paleo proxies and AMOC state using both paleo observations and climate model simulations.
• High-resolution sea level proxies during the Holocene provide a unique opportunity to link the instrumental record with the paleoclimate record if we understand how sea level signals are related to the AMOC. Further development of such records, as well as their interpretation, should continue to be supported.

4.3 Modeling capabilities

The development of a predictive understanding of the AMOC depends heavily on the use of numerical models. In conjunction with observations, models are used to increase our understanding of the mechanisms governing AMOC variability and predictability, as well as the global and regional scale climate impacts of AMOC. Models can also provide important information to guide the design of AMOC observational networks. Further, models are at the heart of any AMOC prediction system.

A wide variety of models continue to be in use today. They range from very simple conceptual models of the AMOC (e.g., statistical models, simple process oriented models) to complex, three-dimensional, high-resolution coupled models. Maintaining such a hierarchy of models is vital to increasing our understanding of the AMOC. Model resolution and computer speed are key limitations, but improving our fundamental understanding of ocean processes and how to represent them in models are key aspects for improving our ability to simulate the AMOC. Some of these important processes include the influence of topography on oceanic flows, overflows, the representation of oceanic convection and mixing (e.g., mesoscale, submesoscale, vertical), and the representation of small-scale shelf processes and their interactions with the open ocean.

Improvements in our representation of these processes, and incorporation of them into state-of-the-science climate models, are crucial. There is also a need for eddy-resolving resolution in the ocean models to properly simulate many processes important to AMOC. The general requirements for sustained modeling-related capabilities were listed and described in detail in the earlier US AMOC reports. As in observational activities to maintain, the modeling activities will remain the same for the foreseeable future. Therefore, only an abbreviated list is provided below for brevity, and further details can be found in the previous reports:

• Maintained support for designing and performing coordinated experiments to investigate robustness of proposed AMOC variability mechanisms and for testing the AMOC response to specific forcings (e.g., NAO, AMV, Southern Ocean winds).
• Maintained support for designing and performing coordinated decadal prediction experiments on AMOC-related climate events.
• Sustained support for both the high-end coupled modeling activities at the large US national laboratories, including NCAR and GFDL, and high-end computers. Enhanced computational power supports use of high-resolution coupled models, particularly with eddy-permitting and/or eddy-resolving ocean components.
• Continued support for process-based and idealized modeling studies within the academic research community.
• Continued support to improve model parameterizations and to incorporate new ones to represent missing physics. These activities should parallel the efforts to increase model resolution and to understand processes better.
• Sustained infrastructure that makes climate model output easily available over the web.
• Support for development and maintenance of infrastructure, analysis tools, and storage capabilities to efficiently enable analysis of large climate model outputs.
• Sustained support to improve ocean data assimilation systems used to estimate the AMOC state in the past few decades. There remain substantial differences in the estimated variability of AMOC state derived from the current generations of assimilation products, especially on decadal timescales. While the lack of direct observations for the past decades contributes to these differences, limitations in understanding model and data errors (which dictate the outcome of the assimilation) are also important. Continuing efforts to improve the representation of the model and data errors of these systems can lead to better consistency and fidelity of the resulting estimation products, which would greatly enhance the potential of using these products to study the mechanisms of AMOC variability.
• Sustained support for assimilation efforts beyond ocean data assimilation, i.e., coupled data assimilation.
5 FUNDING

5.1 FY 2016–17 agency support

NSF, NOAA, NASA, and DOE, the federal agency sponsors of the US AMOC Science Program in FY 2016 through FY 2017, funded a total of 63 projects supporting the work of more than 120 US scientists (listed in Appendix B). Of these projects, 20 were newly awarded in 2016–2017. NSF provided between $7M to $8M in incremental funding annually to 26 projects to observe and document AMOC state and variability, improve understanding of AMOC mechanisms and predictability, and examine the links between AMOC and climate variability. NOAA allocated between $2M and $3M each year to 30 projects to sustain in situ observations, document the state and variability of AMOC, and conduct multi-model analyses and experiments to better understand the mechanisms of AMOC variability and predictability. NASA provided approximately $700K annually to support six projects exploiting satellite observations and data sets, and characterizing the attributes, variability, and mechanisms of the AMOC. DOE allocated approximately $600K for three modeling studies examining the mechanisms of AMOC variability and predictability as well as the influence of AMOC on climate.

The four agencies, through their support of the US CLIVAR Project Office budget, cosponsored the 2017 US AMOC Science Team Meeting held 23–25 May 2017 in Santa Fe, New Mexico.

5.2. FY 2018 outlook

With the completion of 26 projects in FY 2016–2017, there are 37 ongoing US AMOC projects supported by NSF, NOAA, NASA and DOE in FY 2018. NSF will accept new AMOC project proposals through its standard solicitations for the Physical Oceanography and the Climate and Large-scale Dynamics Programs. NASA is soliciting new projects in its ROSES–2018 Research Announcement for analysis and interpretation of the ocean circulation using satellite and in situ data. DOE will accept new projects proposals through its FY 2018 solicitation. NOAA is not soliciting new projects for 2018.

The agencies are providing support to US CLIVAR Project Office to support the 2018 International AMOC Science Meeting, co-sponsored by the UK RAPID Programme, scheduled for 24–27 July 2018 in Miami, Florida.
At inception, the US AMOC Science Team was scoped as a limited-lifetime coordination and implementation entity. It was originally charted as a five-year endeavor in 2008 to address the US Joint Subcommittee on Ocean Science and Technology near-term research priority to understand mechanisms of AMOC leading to new monitoring and prediction capabilities. In 2013, the sponsoring agency programs decided to continue supporting the effort within US CLIVAR for another five years, through 2018. In 2015, the Science Team Executive Committee recommended and the agency managers approved a further two-year extension through 2020, in order to sync with the conclusion of the current UK RAPID project period. December 31, 2020 is the sunset date for the Science Team.

Beyond 2020, AMOC science will continue to be of interest to US CLIVAR and the broader, international community. Agency programs will continue to support AMOC research and infrastructure projects to address the ongoing, pressing science priorities that have been well-honed and articulated by the Science Team. Science sessions at AGU Fall Meeting and Ocean Sciences that have expanded during the past decade can be expected to continue, and the CLIVAR Atlantic Panel will coordinate activities internationally.

During the next two and half years, the Executive Committee, Task Teams, and Project Office will work to complete specific activities, deliver legacy products, review and synthesize scientific advances, clarify ongoing scientific priorities, and hand off coordination functions to appropriate bodies (e.g., CLIVAR Atlantic Panel). The list below identifies a draft set of activities to facilitate the smooth transition to sunset and the responsible parties.

6.1 Priorities
- Revise near- and long-term priorities to reflect ongoing research needs extending beyond the Science Team (TTs)
- Distill a set of programmatic action items to be completed through 2020 (TTs)
- Establish the pathway for transitioning components of AMOC observing system from research to sustained (EC, Program Managers)

6.2 Collaboration
- Convene science meetings (2018, 2020) and coordinate conference sessions (EC, TTs, Project Office)
- Organize Paleo Task Team (Project Office)
- Transition current program-to-program collaborations (e.g., with UK RAPID-AMOC, EU AtlantOS) to US and International CLIVAR panels (EC, Project Office)
6.3 Legacy Products
- Produce capstone special journal collection, including review/synthesis papers and science papers (EC, TTs)
- Produce white paper(s) regarding AMOC observing requirements for Ocean Obs ’19 (TTs)
- Produce metrics for bridging the evaluation of model simulations, renanalyses, and observations (TTs)
- Produce analyses of CMIP6 and CORE simulations of AMOC (TTs)
- Issue final US AMOC Report (2020; EC, Project Office)
- Complete bibliography of US AMOC research papers (Project Office)

6.4 Communication
- Inform the community of the sunset plans, including a town hall at the 2020 Ocean Sciences Meeting to showcase accomplishments, legacy products, and future research needs (EC, Project Office)
- Include discussion of Science Team wrap-up in final two reports (2018 and 2020; EC, Project Office)
- Prepare timeline graphic showing activities for 2018-2020 with indication of ongoing activities beyond (Project Office)
- Prepare graphics highlighting Science Team accomplishments (Project Office)
- Develop an AMOC website structure to showcase accomplishments/legacy using the above content (Project Office)
- Create a general AMOC listserv for the community (Project Office)
REFERENCES


Appendix A: US AMOC Task Teams

Task Team I: AMOC Observing System Implementation and Evaluation

Members

<table>
<thead>
<tr>
<th>Magdalena Andres, chair</th>
<th>Woods Hole Oceanographic Institution</th>
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<tbody>
<tr>
<td>Kathleen Donohue, vice-chair</td>
<td>University of Rhode Island</td>
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<td>Molly Baringer</td>
<td>NOAA Atlantic Oceanographic and Meteorological Laboratory</td>
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<td>Duke University (now at NOIZ)</td>
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<tr>
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<td>Gustavo Goni</td>
<td>NOAA Atlantic Oceanographic and Meteorological Laboratory</td>
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<td>Patrick Heimbach</td>
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<tr>
<td>Bill Johns</td>
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<td>Felix Landerer</td>
<td>Caltech/NASA Jet Propulsion Laboratory</td>
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<td>Isabel LeBras</td>
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<td>Craig Lee</td>
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Institution

The team is charged with the design and implementation of an AMOC monitoring system. AMOC monitoring in the US is currently accomplished by a collection of in situ field programs and large-scale observations including: ARGO, the Global Drifter Array, and collection of satellites returning ocean surface and meteorological information. Near-term priorities for this task team include:

- Improve understanding of the meridional coherence (and/or lack thereof) of the AMOC and the mechanisms that control AMOC variability. Characterize and investigate coherence within the subpolar and subtropical gyres, communication between the gyres, and communication of changes across the equator to the South Atlantic.
- Develop dynamically consistent model-data synthesis methods to combine the heterogeneous observational components.
- Seek new potential funding mechanisms to sustain key elements of the US AMOC observational networks.
• Better characterize the deep ocean to quantify the role of deep temperature and salinity signals that contribute to AMOC variability through enhancements to the observing system that directly measure deep ocean properties (temperature, salinity, and velocity) such as Deep Argo, Deep gliders, and moored instrumentation.

• Ensure that AMOC estimates are made available in widely recognized locations, such as the World Ocean Database, OceanSITES, the National Center for Environmental Information (NCEI), etc. AMOC estimates should be accompanied by their key underlying measurements as well as their error estimates on multiple timescales from weeks to months to years. This allows the necessary information for analyses, inter-array comparisons, and numerical model studies.

• Improve communication within the US AMOC observing system groups and between national and international programs.
Task Team 2: AMOC State, Variability, and Change

Members

Zoltan Szuts, chair
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University of Miami/NOAA AOML
University of Washington
Woods Hole Oceanographic Institution
Woods Hole Oceanographic Institution
University of Washington
University of Delaware
NOAA Geophysical Fluid Dynamics Laboratory

The team is charged with assessing the current state and past variability of the AMOC using existing observations, data assimilation models, and proxy data. Discussions have identified thematically organized questions on which immediate progress can be made based on lack of consensus between different approaches.

AMOC Characteristics

- Depth extent of AMOC cells
- Level of high-frequency variability
- Dominant timescales of variability
- Long-term trends of overturning strength

Coherence between gyres

- Role of planetary waves varies between models in terms of patterns, timing, and forcing
- Balance between high-latitude wind versus buoyancy forcing (observations or models)
- Subtropical/Southern ocean connectivity, including geostrophic reference level
- Nature of coherence in the upper AMOC branch, as related to observational coverage (well-resolved temperature and upper ocean circulation versus poorly sampled salinity and deep ocean)
- Impact of eddies and indirect (and unknown) water parcel pathways, and their resulting transfer between gyres.
• Relation between Eulerian and Lagrangian perspectives of coherence

**Methodological improvements for comparison and synthesis**
• Consistent metrics to compare models and observations, including observational methods and assumptions, and whether calculated in depth or density space
• Quantifying uncertainty in data products
• More explicit synthesis of Eulerian and Lagrangian descriptions of overturning, especially as influencing advective fluxes of climatically relevant quantities (heat, freshwater, carbon, etc.)
The team is charged with assessing the physical mechanisms underlying AMOC variability and the potential predictability of the AMOC. Both natural and anthropogenically-induced variations are being pursued. Near-term priorities for this task team include:
• Investigate how surface exchanges of buoyancy and momentum between the ocean and the atmosphere/cryosphere drive the AMOC circulation across a broad range of timescales from monthly to millennial (i.e., quasi-steady-state).
• Clarify the apparent disagreement between models of different complexity regarding i) the role of Southern Ocean wind and ii) the role of Nordic Seas overflows in maintaining and modulating the AMOC.
• Quantify the magnitude, location, and physical mechanisms associated with interior diapycnal mixing in the ocean, which contribute to the diabatic AMOC, and evaluate the realism of current GCMs in this regard.
• Investigate the role of freshwater forcing and South Atlantic freshwater transports in determining the variability and stability of the AMOC.
• Expand the use of eddy-resolving models, particularly in regional/process studies designed to: i) test the robustness of AMOC variability mechanisms identified in coarser GCMs or idealized models; ii) address the origins of persistent model bias in the North Atlantic region (e.g., Gulf Stream separation and the North Atlantic Current path); and iii) assess the role of ocean turbulence in AMOC variability.
• Quantify the predictability properties of AMOC in idealized and comprehensive models and identify mechanisms that affect these properties.
• Explore the mechanisms associated with AMOC variability on centennial-to-millennial timescales, and evaluate the realism of GCMs on these timescales relative to available paleo proxy data, perhaps using proxy-enabled coupled climate models.
Task Team 4: Climate Sensitivity to AMOC: Climate/Ecosystem Impacts

Members

Martha Buckley, chair  George Mason University
Chris Little, vice-chair  Atmospheric and Environmental Research Inc.
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Rong Zhang  NOAA Geophysical Fluid Dynamics Laboratory

The task team is charged with better understanding the links between the AMOC and North Atlantic SST and teleconnections with climate variability elsewhere. Near-term priorities for this task team include:

Relationship between AMOC, the ITCZ, and the hydrological cycle
Modeling experiments seem to clearly suggest an impact between imposed changes in the AMOC and shifts in the ITCZ. However, ITCZ shifts in coupled models appear to be damped in contrast to slab models. The impact of internal variability of the AMOC on the ITCZ is more uncertain, but there are interesting recent results, including high predictability of shifts in the ITCZ position (Martin and Thorncroft 2015), which seem to be related to changes in the AMOC in the subpolar North Atlantic. However, several key questions remain unaddressed, including:

- What is the impact of model biases on the ability to capture AMOC variability and teleconnections?
- What are the interactions between the AMOC, AMV, and changes in different types of clouds?

Relationship between the AMOC and global and regional sea level
- Does the AMOC and resulting ocean heat transport have a significant impact on regional sea level? How does it compare to other factors (e.g., local winds, changes in the Gulf Stream path)?
Can sea level be used as a proxy for the AMOC?

**Relationship between the AMOC and the cryosphere**
- What are the mechanisms for warming along the ice shelf in Greenland? Related to the AMOC? Local winds?
- What is the impact of the melting of the Greenland Ice Sheet on the AMOC (e.g., Oceans Melting Greenland project)?

**Relationship between the AMOC and climate extremes**
- What is the impact of the AMOC on hurricanes?
- What is the impact of the AMOC on droughts?
- How can the CMIP6 decadal MIPs be used to understand AMOC variability and related climate impacts?

**Relationship between the AMOC, the carbon cycle, and marine ecosystems**
- How does the AMOC impact the carbon cycle?
- What is the impact of the AMOC/AMV on fisheries?
## Appendix B: AMOC Projects Active in 2016/17

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Appendix C: AMOC Project Reports

Western Boundary Time Series

PIs: M. Baringer¹, D. Volkov and S. Garzoli²,¹
National Collaborators: B. Johns², and C. Meinen¹,
International Collaborators: D. Smeed³, B. Moat³, D. Rayner³, H. Bryden³ and G. McCarthy³
¹NOAA Atlantic Oceanographic and Meteorological Laboratory
²University of Miami
³National Oceanography Centre, UK

This project continuously monitors two important components of the thermohaline circulation in the subtropical North Atlantic with the ultimate goal of determining the state of the overturning circulation and providing a monitoring system for rapid climate change and hence addresses the program deliverable on “OHC and transport.” The components include the northward flowing Florida Current and the southward flowing DWBC.

Recent results
The seasonal variability of the Florida Current transport exhibits year-to-year changes during the 1983–2013 record. Year-to-year changes in the Florida Current seasonality are linked with westward propagating signals originating in the eastern North Atlantic. Coastal sea level changes forced by westward propagating signals account for ~50% of the FC seasonal variability that is linked with variable annual phase. Domingues et al. (2016) showed that these westward propagating features offer a mechanism for providing a seasonal outlook of coastal sea-level variations.

The quasi-quarterly CTD/LADCP sections across the Florida Current onboard the FG Walton Smith provide useful information for calibrating the cable voltage observations, but the CTD and LADCP data can also provide useful scientific information on long-term ocean changes as a result of the long history of observations in the Florida Straits at 27°N. Szuts and Meinen (2017) used 55 cruises during 2001–2015 to evaluate the Florida Current salinity transport within different water mass classes, and they also compared these observations to measurements made in the 1980s at the same locations to evaluate how the different water masses carried by the Florida Current have changed over the ~20 years between the two periods. These observations provide insights into how the overturning and gyre contributions to the Florida Current vary, and they illustrate the importance of observing water properties in the Florida Current in addition to the volume transport.
The “State of the Climate” report continues to highlight the long-term ocean circulation variability measured in the WBTS project. In Baringer et al. (2017), it was noted that Florida Current transport has decreased from 1982 to 2016 by $-0.30 \pm 0.24$ Sv per decade (errors estimating 95% significance as above) in spite of a slight increase in annual average transport for 2016 ($31.8 \pm 1.9$ Sv). High frequency variations in the Florida Current were shown to be inversely related to local sea level variations with more than 99% confidence (high coastal sea level corresponding to low Florida Current transport). These variations in Florida Current contribute to the trends seen in the MOC and MHT computed from the transatlantic mooring array at 26°N that suggest an MOC/MHT decrease of $-3.0 \pm 2.4$ Sv per decade/$-0.23 \pm 0.19$ PW per decade.

Data are available online:
- NOAA Florida Current and cruise data: [http://www.aoml.noaa.gov/phod/wbts/data.php](http://www.aoml.noaa.gov/phod/wbts/data.php)
- Merged with MOC data: [http://www.noc.soton.ac.uk/rapidmoc/](http://www.noc.soton.ac.uk/rapidmoc/)
- Merged with Heat transport data: [http://www.rsmas.miami.edu/users/mocha/](http://www.rsmas.miami.edu/users/mocha/)

Bibliography

**Figure:** Baringer et al. (2017) show estimates of the MOC in the Atlantic Ocean from the Argo/Altimetry estimate at 41°N (black; Willis 2010), the RAPID-WATCH/MOCHA/WBTS 26°N array (red; Cunningham et al. 2007), and the German/NOAA MOVE array at 16°N (blue; Send et al. 2011) are shown versus year. All time series have a three-month second-order butterworth low pass filter applied. Horizontal lines are the mean transport during similar time periods as listed in the corresponding text. Dashed lines are the trends for
each series over the same time period. For the MOVE data the net zonal and vertical integral of the deep circulation represents the lower limb of the MOC (with a negative sign for the southward flow), and hence a stronger negative southward flow represents an increase in the MOC.

Understanding drivers and impacts of CGCM biases in representing the decadal variability of Labrador Sea convection

**PIs:** A. Bracco and T. Ito  
**Graduate student:** F. Tagklis  
**Georgia Institute of Technology**

The overarching objectives of this project are to diagnose the sources of coupled GCMs’ biases in the Labrador Sea focusing on a subset of CMIP5 runs and to quantify the impacts of those biases on the representation of carbon and oxygen uptake and inventories in the basin. This will be achieved through an analysis of CMIP5 Earth System Models (EaSM) and a sensitivity study performed using ROMs covering most of the North Atlantic forced by momentum, heat, and freshwater fluxes, and/or boundary conditions from the CMIP5 runs.

**Recent results**

We completed the analysis of the CMIP EaSM runs and published a first paper describing major outcomes (Tagklis et al. 2017). The focus of the analysis was on the upper 700 m of the North Atlantic Ocean. It was found that the climatological distributions of dissolved O₃ averaged over the recent past period (1975–2005) were generally well captured, although the convective activity differed among the models in space and strength. By the end of the 21st century, all models predict an increase in depth-integrated temperature of 2-3°C, resultant solubility decrease, weakened vertical mass transport, decreased nutrient supply into the euphotic layer, and weakened export production. Despite an overall tendency of the North Atlantic to lose oxygen, patchy regions of O₂ increase characterized some of the models due to the weakening of the North Atlantic Current causing a regional solubility increase (the warming hole effect) and a decrease in the advection of subtropical, low-O₂ waters into the subpolar regions (the nutrient stream effect). Additionally, a shift in the North Atlantic Current position was found to contribute to localized O₂ changes near the boundaries of water masses.

We are performing the first set of ROMS runs with a two-way nested configuration achieving 5 km in the Labrador Sea and 15 km elsewhere with 50 vertical layers. The validation of the run indicates a very good agreement with available observations in terms of the physical representation of mixed-layer depth, the seasonality of deep convection, and the overall density structure. We are currently tuning the biogeochemical model (Figure).
We are investigating the role of submesoscale variability in modifying primary productivity and transport of meltwater with two sets of integrations at 2.5 and 1 km horizontal resolution limited to the years 2008 and 2012. This portion is in collaboration with R. Castelao at University of Georgia.

We generated a first suite of forcing files from two CMIP5 EaSM models that will be used to force ROMs, once a preliminary investigation of the role of horizontal resolution is completed.

**Bibliography**

**Figure:** (top) Model domain for control run highlighting the two-way nested region at 5 km resolution of the Labrador Sea. (bottom) Annual cycle of mixed-layer depth averaged over the period Jan. 1950– Dec. 1958.
Identifying mechanisms of AMOC variability in ECCO state estimates and CMIP5 models

PIs: M. W. Buckley\(^1\), P. Heimbach\(^2\), and R. M. Ponte
\(^1\)George Mason University
\(^2\)University of Texas, Austin
\(^3\)Atmospheric and Environmental Research Inc.

The goal of this project was to use ECCO ocean state estimates and CMIP5 models to understand the connections between variability in the Atlantic Ocean circulation and heat content in the North Atlantic. Our recent work was focused on three main areas, as detailed below.

**Origin of North Atlantic subpolar gyre ocean heat content changes**
We performed a detailed analysis of the OHC trend reversal from warming to cooling that was observed around 2004–05 in the subpolar North Atlantic (Figure a,b). Closed heat budget diagnostics of the ECCO estimate reveal that the observed OHC trend reversal is primarily related to heat advection by the mid-latitude ocean circulation (Figure c). Kinematic decompositions show that ocean heat transports by anomalous horizontal gyre flows acting on mean temperature gradients are the primary contributors to the OHC trend reversal in the subpolar North Atlantic, with effects of deep and intermediate vertical overturning circulation playing a secondary role. Maximum covariance analysis indicates that the anomalous horizontal gyre circulation was tightly coupled to variations in the local wind stress curl, suggestive of a Sverdrup response.

**Dynamical reconstruction of AMOC variability at 34°S**
Using the adjoint model available within the ECCO framework, we reconstruct AMOC variability at 34°S via adjoint-generated linear sensitivity fields. The method affords offline calculation and decomposition of AMOC variability with respect to its various forcing terms, as a function of timescales. The reconstruction isolates pathways and linear dynamics between applied surface forcings and the impact on the transport variability at 34°S at various lead times. We find that local wind stress dominates variability at subannual timescales (including seasonal timescales) and that buoyancy forcing plays a relatively minor role, confirming results from past forward sensitivity experiments. Interannual variability during this time period, however, is shown to have significant contributions from remote locations across the globe.

**Predictability of upper ocean heat content in ocean data products and CMIP5 models**
Prior results indicate that i) the North Atlantic is a region with enhanced predictability of SST related to ocean initialization and ii) predictability timescales vary substantially between models. Motivated by this, we diagnose predictability timescales of upper OHC from i) ocean data products and ii) control runs of CMIP5 models. We find:
- Predictability timescales of upper OHC are longest in the subpolar gyre.
- Analysis of ocean data products shows no evidence of periodic behavior of upper OHC, at least on the timescales resolved by these products (extend from 1945 to present). In contrast, some models (e.g., GFDL CM3 and ESM2M) have regions with strong periodicity in upper OHC.
• In ocean data products, spatial variations in predictability timescales are strongly related to spatial variations in the climatological wintertime mixed layer depth. In CMIP5 analyses, some models have strong relationships between predictability timescales and the climatological wintertime mixed layer depth (e.g., CCSM4), while the relationship is much weaker in other models (e.g., CM3 and ESM2M).

**Bibliography**


**Figure:** (a) Difference in linear trend of upper OHC between cooling (2005–2015) and warming (1994–2004) periods in the North Atlantic subpolar gyre. Upper OHC is computed from Met Office Hadley Centre EN4.2.0 temperatures (top 700 m; Good et al. 2013). Thick black outlined box delineates the SPNA control volume. To emphasize regional behavior global mean UOHC time series have been removed at each spatial grid point prior to trend calculations. Thin black contours are zero crossings. All panels have units of °C yr⁻¹. (b) UOHC from Met Office Hadley Centre EN4.2.0 observations [Good et al. 2013] (black) and ECCOv4 (blue) over the SPNA. Thick dark lines represent OHC integrated over the top 700 m while thin pale lines represent OHC integrated over the full water column depth. To emphasize decadal anomalies, all time series have been detrended and seasonally adjusted. (c) Full-depth OHC budget for the SPNA. Total OHC (T; black) along with advection (A; gray), diffusion (M; red), and forcing (F; yellow) budget contributions.
The Western Transition Zone as a Gatekeeper for the North Atlantic MOC Throughput

PIs: M. W. Buckley¹ and S. Lozier²
¹George Mason University
²Duke University

This project focuses on the mechanisms controlling the transport between the subtropical and subpolar gyres, which is integral to understanding variability of the AMOC. Our hypothesis is that AMOC variability mechanisms can be understood with a focus on the dynamics at the western margin of the subtropical-subpolar gyre boundary, a region we refer to as the Western Transition Zone (WTZ). We aim to answer the underlying question: Can the WTZ be understood as a gatekeeper for the throughput between the subtropical and subpolar gyres? Thus far our work¹ has focused on i) a Eulerian analysis to understand how and in what layers AMOC anomalies are communicated between the gyres and ii) a Lagrangian analysis aimed to determine the pathways through the WTZ and how these pathways change based on density anomalies in the WTZ.

Communication of AMOC anomalies between the subtropical and subpolar gyres
Motivated by the RAPID observations showing that AMOC anomalies are correlated with anomalies in the lower NADW (Figure a), we use a variety of models to study the relationship between AMOC and the transport anomalies in different layers of the lower limb at other latitudes spanning the subtropical and subpolar basins. Our main conclusions are as follows:

• Both the upper NADW and the lower NADW layers are important in interannual AMOC variability in the subpolar gyre. In the subtropical gyre, most of the AMOC variability is contained in the lower NADW layer (Figure a-c).
• There is no coherent propagation of the transport anomalies from the subpolar gyre to the subtropical gyre in upper NADW layer.
• On interannual timescales, there is no coherent propagation of transport anomalies between the gyres in the lower NADW layer, except during “events” in which there are very strong subpolar anomalies.

Lagrangian Pathways through the WTZ
We computed five-year forward and backward trajectories for parcels released in the Labrador Sea Water and overflow water layers in the WTZ. Backward trajectories indicate that over the five-year period prior to their arrival in the WTZ, both Labrador Sea Water and overflow water are most likely to be in the western subpolar gyre, including the Labrador Sea, or recirculating in the WTZ region. Furthermore, when densities are high in the WTZ, waters are more likely to have been in the Labrador Sea; while when densities in the WTZ are low more water recirculates. Forward trajectories demonstrate that a large portion of floats released in the WTZ recirculates in this region; some enter the western part of the subpolar gyre, while others enter the western part of the subtropical gyre. When densities are high in the WTZ, a larger portion of the floats travel southward into the subtropical gyre along the western boundary. Current work is focused
on determining the mechanisms behind these trajectory differences as well as developing a quantitative measure of the throughput in the Lagrangian frame.

*Much of the work on this project was completed by S. Zou, a graduate student at Duke funded by this project.

**Figure:** (a, top) Time series of monthly AMOC anomalies (blue), transport magnitude anomalies in the upper NADW layer (orange), and transport magnitude anomalies in the lower NADW layer (yellow) at RAPID line (26.5°N). The time series are deseasonalized and smoothed with a one-year filter. (a-c, bottom panels) Correlation as a function of latitude between the AMOC and transports in the upper NADW and lower NADW layers for (a) FLAME (1990–2004), (b) ORCA025 (1961–2004), and (c) SODA2.2.4 (1961–2009). Figures are from S. Zou (Duke U.).
Collaborative Research: Understanding Changes in the AMOC During the 20th Century Using IPCC AR5 Model Ensembles

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The objectives of this collaborative research between Texas A&M University and NCAR are i) to understand the dominant ocean-atmosphere processes controlling the long-term AMOC changes over the 20th century and examine how these processes are represented in the models contributing to the IPCC AR5, and ii) to determine plausible causes of differences in long-term AMOC changes simulated by coupled climate models and forced ocean-sea ice models during the late 20th century. The proposed research consists of a comprehensive inter-model comparison analysis of coupled climate model simulations contributing to IPCC AR5, ocean-sea ice model simulations of the 20th century climate, and a set of ocean-sea ice model sensitivity experiments to assess the sensitivity of long-term AMOC changes to a variety of alternative atmospheric state choices.

Recent results
Our research activity during the past year focused on a comprehensive analysis of AMOC trends and variability during the 20th century from the CESM-LE and forced ocean-sea ice hindcast simulations, i.e., CORE-II. We have found that the simulated low-frequency AMOC variability in CESM-LE is underestimated compared to that simulated in CORE-II. We attribute this difference to the weaker than observed low-frequency variability of the NAO in CESM-LE. We further show that as a result of the weak low-frequency AMOC variability, low-frequency variability of many other key climate variables in the North Atlantic is also weaker than their respective observed estimates (Figure). These include the subpolar North Atlantic SST and Sahel summer rainfall variability, which have been linked to low-frequency AMOC changes in many previous modeling studies. It is evident that CESM-LE reveals a weaker than observed power on multidecadal timescales.

The weaker than observed low-frequency NAO variability in CESM-LE could be due to biases in SSTs, i.e., the surface boundary conditions for the atmospheric model and/or poorly resolved model stratosphere. However, further analysis indicates that these do not appear to be the cause, because even when the atmospheric component of CESM-LE, Community Atmospheric Model version 5 (CAM5), is run with observed time-varying SSTs as lower boundary conditions or with a better represented stratosphere, in addition to the observed boundary conditions, the simulated low-frequency NAO variability is still too weak, similar to that from CESM-LE. Furthermore, the simulated low-frequency NAO variability is not distinguishable from what can be obtained from pure white noise. These results, therefore, suggest that the weak low-frequency NAO variability in CESM-LE is likely attributable to deficiencies in CAM5 itself (such as horizontal/vertical resolution and parameterized physics) and/or coupling methods, rather than boundary conditions or poorly resolved stratosphere. These findings and further details are documented in Kim et al. (2018).
Bibliography

**Figure:** Power spectrum of the annual (top left) AMOC, (top right) subpolar North Atlantic SST, (bottom left) summer (Jun-Sept) Sahel rainfall, and (bottom right) winter (Dec-Mar) NAO from CESM-LE (blue shading: ensemble spread; blue line: ensemble mean) and observations (solid red line). The ensemble mean is removed from CESM-LE and the power spectrum after removing the CESM-LE ensemble mean from the observations is also shown in red dashed line. The yellow shading highlights the low-frequency band where CESM-LE substantially underestimates the observed variance.
The goal of this project is to understand how the freshwater budget of the Atlantic Ocean is controlled by interconnections between surface forcing and oceanic transport of freshwater/salt; and how they affect and are influenced by AMOC variability on decadal to multidecadal timescales. We address this objective through a three-prong approach: 1) analyzing existing Earth system model simulations with differing parameters; 2) performing targeted perturbation experiments using the CESM; and 3) online and offline passive tracer simulations using CESM. During the first year of the project, we have focused on examining the so-called salt-advection feedback, which is believed to be an important mechanism for AMOC stability and variability.

**Recent results**

Based on simple box models of AMOC, the sign of the freshwater transport across the southern boundary (at 33°S) of the Atlantic Ocean by AMOC – commonly referred to as Fov – has been suggested as an indicator for AMOC stability. The associated mechanism is usually referred to as the salt-advection feedback, and it critically depends on three components: 1) the AMOC strength is influenced by the meridional density difference between the North Atlantic and South Atlantic (Δρ_N-S); 2) the AMOC strength influences Fov; and 3) Fov in turn feeds back onto AMOC. In such a conceptual model framework (Figure, left panel), when AMOC is stronger, it induces a change in Fov through perturbing the local meridional velocity vertical distribution. Thereon, the feedback loop splits into two depending on the sign of Fov. When it is positive, a stronger AMOC transports more freshwater into the Atlantic Ocean and freshens it (i.e., reduced Δρ_N-S), and as a result, AMOC decrease; in this case, the salt-advection feedback is negative and has a stabilizing effect on AMOC (mono-stable regime). Conversely, when Fov is negative, a stronger AMOC transports more freshwater out of the Atlantic Ocean and makes it saltier (i.e., increased Δρ_N-S), and thus strengthens the AMOC; in this case, the salt-advection feedback is positive and it destabilizes AMOC (bi-stable regime). Using pre-industrial control simulations from GFDL-ESM2M and CESM1, we have investigated whether any evidence exists to support this feedback mechanism in more realistic Earth system models.

Both ESMs have large salinity biases throughout the Atlantic, typical of most climate models. These salinity biases, occurring both in the upper ocean (above 800 m) and at depth (1.2-4 km) cause Fov to have a positive bias. The modeled decadal and longer timescale variability of Fov(y) (i.e., freshwater transport by the AMOC at any latitude) is dominated by variability in the salinity field rather than in the velocity field, except in the northern subtropics (15°–45°N) where the velocity...
variability dominates. Therefore, Fov decadal variability co-varies more with the region’s salinity variability than with its AMOC variability. Similarly, we do not find any evidence for Fov changes influencing the strength of AMOC on these timescales. Based on our findings, we provide a revised version of the salt-advection feedback in the right panel of the Figure. Specifically, the link from AMOC to Fov occurs via two mechanisms: change in meridional velocity vertical structure (which works on model mean salinity with biases) and change in salinity vertical profiles. We find that the effect of the latter to be stronger than the effect of the former. We do not find any evidence to support a link between Fov and $\Delta \rho_{N-S}$. Finally, AMOC variability leads slightly $\Delta \rho_{N-S}$ variability, suggesting that AMOC drives changes in the latter, and the north-south density difference is $\rho_{N-S}$ also begs the question of potentially two-way interactions between AMOC and density variations in the North Atlantic. Our findings are detailed in Cheng et al. (2018).

**Bibliography**


**Figure:** Schematic of the basin-scale salt-advection feedback. Small circles represent (clock-wise from the top): AMOC at 45°N, Fov at 33°S, North Atlantic-South Atlantic density difference ($\Delta \rho_{N-S}$), respectively. AMOC at 45°N is used as an AMOC index.
A Collaborative Multi-Model Study: Understanding AMOC Variability Mechanisms and Their Impacts on Decadal Prediction

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This collaborative project between GFDL, NCAR, and WHOI is aimed at advancing our understanding of simulated AMOC variability, the impact of that variability on the atmosphere and climate, and the relevance of that variability to our ability to make decadal climate predictions.

Recent results
We performed three new studies using an extensive database of multi-model output from our idealized AMV experiments, expanding upon our initial study that focused on the global impacts of AMV (Ruprich-Robert et al. 2017). In these coordinated experiments with the GFDL-CM2.1, GFDL-FLOR (Forecast-oriented Low Ocean Resolution), and CESM1 (Community Earth System Model version 1) climate models, the model daily SST are restored to the observed intrinsic AMV anomalies superimposed on the models’ own daily climatology over the North Atlantic. By only perturbing the North Atlantic sector of the coupled models, our set-up permits estimation and isolation of the full climate response to the observed AMV forcing. Because we aim to assess the effects of internal variability, all experiments use pre-industrial conditions, where all external forcings are maintained constant at their 1850 levels. To obtain reliable estimates of the impacts of AMV, a large number of ensemble simulations are performed with 30, 100, and 50 members for CESM1, CM2.1, and FLOR, respectively. For the AMV+ (AMV-) ensembles, SST anomalies corresponding to one standard deviation of the AMV index are added to (subtracted from) the model climatological SST. We use 10-year simulations because they are long enough for the responses to atmospheric teleconnections associated with AMV-like SST perturbations to arise, yet short enough to limit drift issues in the NA associated with the dynamical adjustment of the ocean to the imposed SST perturbations. Further details of the experimental protocol are presented in Ruprich-Robert et al. (2017).

The first new study targets the impacts of AMV on North American surface climate, with a special focus on heat waves and temperature extremes (Ruprich-Robert et al. 2018). All models show that AMV+ is associated with reduced precipitation and warming over northern Mexico and the southern US (Figure 1). This warming is responsible for a 30% increase in the number of heat wave days. We have found that the positive tropical Atlantic SST anomalies associated with AMV+ drive a Matsuno-Gill-like atmospheric response that favors subsidence over northern Mexico and the southern US. This leads to warming and humidity divergence in the atmosphere, resulting in
decreases in atmospheric relative humidity, cloud cover, and precipitation. More arid conditions are associated with increased surface air temperature and a greater occurrence of heat waves. Land surface interactions also play a role in the modulation of heat wave occurrence by AMV. In addition, we have identified an indirect impact path in which Atlantic SST changes induce SST changes in the Pacific, and these in turn set up additional teleconnection pathways from the Pacific to North America. This non-direct AMV teleconnection highlights the importance of using fully coupled ocean-atmosphere models to fully assess the AMV impacts on North America. A model with prescribed SST anomalies would not be able to capture this indirect pathway. Given the potential predictability of AMV, the teleconnections discussed here imply a source of predictability for North American climate variability and for the occurrence of heat waves at multi-year timescales.

The second study (Castruccio et al. 2018) focuses on the impacts of the AMV anomalies on the Arctic sea ice via atmospheric teleconnections. We find robust differences in ice thickness between the AMV+ and AMV- ensemble simulations, with all three models simulating thinner sea ice during AMV+. Our analysis shows that thinning in sea ice results from shifts in atmospheric circulation patterns over the Arctic in a very similar manner in all three models (Figure 2). The reduction in the Beaufort high pressure during AMV+ leads to a corresponding reduction in the strength of the Beaufort gyre. We have also identified a dipole response in SLP during the spring with anomalous high (low) SLP on the North American (Eurasian) side of the Arctic. Both anomalous SLP patterns create surface wind anomalies that lead to anomalous ice motions during AMV+, pushing the old multi-year ice out of the Arctic and increasing the ice export through the Fram Strait, thus resulting in younger and thinner ice. The thinner ice, which is more prone to melt, leads to less extensive sea ice at the end of the melting season.

The third study examines if there is a potential role of AMV in driving multi-decadal blocking variability in the NA. This is investigated using both the NCEP 20th Century Reanalysis (20CR, 1900-2010) and CESM1 AMV simulations. Based on a statistical analysis of the 20CR, a significant influence from SST variability associated with AMV is found when AMV+ leads the anomalous dipole blocking pattern by 3-10 years, with more frequent blockings near Greenland and less near the Azores (Figure 3a). This anomalous blocking pattern projects well onto the second empirical orthogonal function pattern of the winter blocking days and is associated with the negative phase of the North Atlantic Oscillation (NAO). The reduced meridional gradient of SST due to the maximum warming associated with AMV is found to drive southward shifts in the storm track and eddy-driven jet, resulting in the anomalous dipole-blocking pattern. In addition, this relationship with AMV is substantially asymmetric and thus only robust in the AMV+ phase. A consistent relationship between AMV and blocking is also found in the idealized AMV experiments with CESM1, as shown in Figure 3b.

In addition to the above AMV-related studies, NCAR and GFDL have recently begun running, analyzing, and comparing results from a suite of fully coupled sensitivity experiments designed to isolate the effects of NAO-related Labrador Sea Water formation anomalies on Atlantic Ocean circulation, SST, and far-field surface climate. Inspired by the idealized NAO-forcing experiments of Delworth and Zeng (2016) and Delworth et al. (2016), these Labrador Sea forcing experiments consist of fully coupled ensembles in which an observation-based NAO air-sea heat flux anomaly
is applied to the ocean model within a limited Labrador Sea domain. The intent is to investigate the role of NAO-related thermohaline ocean dynamics in modulating Atlantic Ocean heat transport and SST, while allowing for natural (i.e., unperturbed) air-sea exchanges throughout most of the Atlantic domain. Such experiments are a useful tool for unraveling the relative importance of ocean dynamics versus direct atmospheric forcing in setting up AMV surface fingerprints. An intriguing early result is that persistent NAO heat flux forcing over the Labrador Sea results in a warming of the subpolar North Atlantic after several years delay. While this result is consistent with inferences about the climate impact of NAO-driven ocean heat transport made from analyzing fully coupled control simulations, it also highlights the role of circulation anomalies, in particular, in driving high-latitude changes.

Bibliography

**Figure 1:** June-July-August averaged 2 m air temperature differences between AMV+ and AMV-. (a) Observed temperature composite difference between the positive and the negative years of the observed AMV index. The temperature data comes from HadCRUT4 and have been linearly detrended. Temperature differences between the 10-year ensemble mean average of the AMV+ and AMV- experiments of (b) CM2.1, (c) CESM1, and (d) FLOR. Stippling indicates regions that are below the 95% confidence level of statistical significance according to a two-sided t-test.
Figure 2: Differences between the AMV+ and AMV- ensemble simulations in (left panels) 10-year winter (Dec-Mar) average geopotential height at 500hPa (contour in m) and its departure from the zonal average (shading in m); (middle panels) 10-year winter average SLP (in mbar) with the resulting anomalous winds overlaid; and (right panels) 10-year average SLP (in mbar) with the resulting anomalous winds overlaid for CESM1 in March, and FLOR and CM2.1 in April. For all columns, panels are for CESM1 (top), FLOR (middle) and CM2.1 (bottom). In the left panels, stippling indicates regions that are significant above the 95% confidence level based on a two-sided Student’s t-test.

Figure 3: Anomalous number of blocking days per winter (Dec-Mar) driven by AMV+ anomalies from (a) the lag-regression using 20CR dataset when AMV leads the blocking by four years and (b) a 10-member ensemble of the CESM1 idealized AMV experiments. Red (blue) contours indicate more (less) frequent blocking. Gray shadings are for the anomalies significant at 95% level. Contour intervals are 1 and 0.5 days per winter in (a) and (b), respectively.
Collaborative Research EaSM2: Mechanisms, Predictability, Prediction, and Regional and Societal Impacts of Decadal Climate Variability

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The goals of this interdisciplinary collaborative project are: i) to produce an improved and reliable decadal prediction system within the CESM framework, including predictive capabilities for marine ecosystems and biogeochemical constituents; and ii) to advance the use of decadal prediction simulations in regional and societal impact studies. To achieve these goals, we are engaged in advancing our understanding and technical capabilities in four fundamental areas related to decadal prediction: i) improving our understanding of intrinsic decadal variability and mechanisms; ii) assessing the inherent predictability constraints of our forecast model; iii) evaluating practical forecast system design methods; and iv) generating capabilities for incorporating fully-coupled data assimilation and ocean ecosystems and biogeochemistry into our decadal prediction system.

Recent results
The role of the AMOC, and more specifically the buoyancy-driven circulation of the North Atlantic, in underpinning Atlantic decadal climate variability and predictability was reviewed recently by Yeager and Robson (2017). The review presents an overview of our understanding of AMV; highlights the promise of decadal prediction in the Atlantic sector; and discusses some of the outstanding questions and future prospects for initialized prediction of near-term climate change. The CESM decadal prediction (CESM-DP) system has recently been significantly improved and expanded increasing its value to the community as a resource for decadal prediction research. The CESM-DP system uses the same code base and external radiative forcings as in the CESM-LE of historical simulations (Kay et al. 2015). A recent multi-model analysis shows that CESM-DP skill in the North Atlantic is quite impressive compared to other systems (Figure 1). The CESM-DP simulation set was expanded to a 40-member ensemble set thanks to an Accelerated Scientific Discovery award of computer time on NCAR’s new Cheyenne supercomputer. The Accelerated Scientific Discovery project, led by Yeager, finished integrations in March 2017 and is now focused on addressing two key science questions: i) How does ensemble size impact the assessment of decadal prediction skill, and ii) Are there predictable shifts in the probability of extreme weather events associated with (predictable) interannual-to-decadal SST and sea ice extent variations. The combination of CESM-DP-LE and CESM-LE offers unprecedented capabilities for discriminating between the forced and initialized components of decadal prediction skill. A particularly promising result is the high skill seen in predicting summertime Sahel precipitation on decadal timescales in CESM-DP-LE (Figure 2). The skill improvement over CESM-LE makes it clear that initialization of AMOC-related ocean heat transport anomalies is key, and the improvement over
CCSM4-DP highlights the improvements made in the system. The CESM-DP-LE includes active biogeochemistry, and preliminary results indicate that there is promising skill at predicting decadal changes in key components of the ocean biosphere that could have important societal impacts. An overview of the CESM-DP-LE as a community resource is provided in Yeager et al. (2018).

In a recently completed study (Frankignoul et al. 2018), two large ensembles of historical climate simulations (IPSL-CM5A-LR and CESM1) are used to compare how well various statistical methods estimate SST changes due to external and anthropogenic forcing. Furthermore, the internally generated AMV and PDV, and the SST footprint of the AMOC, are examined after the external forcing is removed. Two methods based on LIM, a version where the first LIM mode represents the forced signal and another based on an optimal perturbation filter (LIMopt), perform consistently well. Removing the forced signal by subtracting the global mean SST or using a linear regression method (REGR) leads to large errors in the Pacific. Multi-dimensional ensemble empirical mode decomposition (MEEMD) and quadratic detrending efficiently remove the forced SST signal in only one large ensemble, and the method cannot separate the short-term response to volcanic eruptions from natural SST variations. Removing a linear trend fares poorly. In three observational SST reconstructions for the 1900–2015 period, linear and quadratic detrending, MEEMD, and global mean produce somewhat different AMV spatial and temporal structures, and REGR yields smaller PDV amplitudes. Hence, LIM and LIMopt are recommended. However, the first two LIM modes are sometimes needed to represent the forced SST signal, hence LIMopt appears to be a more robust statistical technique to estimate SST changes due to external and anthropogenic forcing. In both large ensembles, the AMV seems largely driven by AMOC in the subpolar North Atlantic but not in the subtropics and tropics (Figure 3), and there is a large scatter in AMOC-AMV correlation in individual ensemble members (not shown).

As explained in earlier reports, by using the fluctuation dissipation theorem (FDT) we have developed a tool for systematically studying the impact of anomalous external forcing on the coupled ocean-atmosphere system. We have applied this tool to the problem of forcing AMOC anomalies on multi-year timescales and have discovered that there are patterns of surface buoyancy fluxes that are much more effective at forcing AMOC than are commonly occurring fluxes. For example, the most effective North Atlantic heat flux pattern is more than twice as effective as NAO heat fluxes at driving AMOC. Here, we highlight two attributes of these special flux patterns that we have recently studied. First is the fact that the influence of forcing events lasts well beyond the duration of the forcing. Our investigation is carried out within the context of the Community Climate System Model version 4 (CCSM4). If we force the model for five years with the pattern of surface heat fluxes that gives the largest response per unit forcing, by year 5 a distinctive AMOC monopole response has been produced (Figure 4a). If we then continue the experiment but with the anomalous heat fluxes removed, we find the AMOC anomalies not only persist but actually continue to grow for several years (Figure 4b), indicating the importance of internal processes as well as the potential for substantial delays in the impact of atmospheric events on AMOC. The second attribute concerns the atmospheric circulation patterns that can produce large AMOC responses. When we have investigated the sea level pressure anomalies that accompany, and presumably are responsible for, the most effective surface heat flux pattern, we find it is a distorted version of the NAO. This implies that secular changes in external conditions
that may affect the structure of NAO events can also potentially have substantial impacts on the statistics of AMOC multi-year variability.

Research on the predictability of extreme weather for societal impact has focused on investigating the predictability of the extreme winter weather patterns over the continental North America for the winters from 2013 to 2016. In the winter of 2014/15, the North America continent experienced a remarkable climate with an east-west dipole anomalous pattern: Several states in the east reported record-breaking cold temperature and blizzard conditions; while states in the west reported record high temperatures, with the seasonal temperature anomalies shown in Figure 5a. Extreme cold days in the east and extreme warm days in the west during the winter are shown in Figure 5b, using the 90th percentile coldest daily temperatures in the east and the 90th percentile warmest daily temperatures in the west. Through ensemble simulations, we have found that the anomalous weather pattern in the winter of 2014/15 is primarily caused by internal variability of the atmospheric circulations. The observed winter season climate is found to be a probable but low probability event. This is in contrast to the predictability of winter weathers in 2013/14 and in 2015/16, whose seasonal temperature anomalies are shown in Figure 5c,d. For these two winters, anomalies in SST and sea ice are found to dominate seasonal climate anomaly patterns that are similar to observations. Results suggest that some anomaly patterns in SST and sea ice carry more predictable information on extreme climate than others, and that probabilistic extreme climate prediction is necessary since low-probability events may occur in reality. Results of this research are published in Xie and Zhang (2017).

**Bibliography**


**Figure 1:** Correlation skill of upper 500 m OHC in the subpolar gyre region (50°–65°N; 60°–10°W) as a function of lead time from various initialized decadal prediction systems: CESM1-DP (cyan), HadCM3 (orange), HiGEM (red), MPI (black), EC-Earth (brown, green, and yellow for “ull-field low-res, anomaly low-res, and high-res, respectively), IPSL (blue). The skill associated with persistence is shown in purple. The observational data set used is Met Office EN4. The different panels compare skill calculated on a level playing field for those systems having start dates every five years (top left), every year (top right), every two years (bottom left), and every year over the modern period (bottom right). Figure courtesy Jon Robson.

**Figure 2:** Prediction skill (anomaly correlation coefficient) as a function of forecast lead-time for boreal summer precipitation (July-Sept) over the Sahel region of West Africa. Skill scores from four different forecast methods are shown: persistence (PERS), CESM-DP-LE (40-member ensemble), CCSM4-DP (10-member ensemble), and CESM-LE (40-member ensemble).
Figure 3: (a-b) Mean AMV pattern after removing the externally forced signal estimated by the LIMopt method from each ensemble member of the large ensemble simulations from (a) IPSL-CM5A-LR and (b) CESM1, respectively. (c-d) Corresponding mean AMOC fingerprint. All are in °C.

Figure 4: Annual mean response of AMOC in CCSM4 when forced for five years by the optimum pattern of surface heat fluxes.

Figure 5: (a) Mean surface temperature anomaly in DJF of 2014/15 (°C), (b) daily temperature anomaly of the 90th percentile coldest days in the east and 90th percentile warmest days in the west in DJF 2015, (c) same as in (a) except for the winter of 2013/14, (d) same as in (a) except for the winter 2015/16.
Pathways to the Denmark Strait Overflow: A Lagrangian Study in the Iceland Sea

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This project aims to elucidate the circulation of dense waters, which supply overflow water to the Denmark Strait and Iceland-Faroe overflows, in the Iceland Sea using acoustically tracked RAFOS floats. A total of 52 floats were deployed in summer 2013 and 2014, at approximately 600-800 m depths, resulting in a total of 40.9 float-years of track data covering the Iceland Sea basin (de Jong et al. 2018). The RAFOS deployments were spread out over the interior Iceland Sea and the east Greenland and northern Iceland slopes. In the interior Iceland Sea basin, the float tracks showed a double gyre circulation, out of which floats eventually escaped towards the Norwegian Sea in the East Icelandic Current, with some appearing to be on route to the Faroe Bank Channel. Four floats deployed west of the Kolbeinsey Ridge at 70°N show the connection between the East Greenland Current and the East Icelandic Current. Floats deployed just north of the Icelandic slope were captured in the eddy rich region in the south corner of the east flank of the Kolbeinsey Ridge. Four floats exited through Denmark Strait and surfaced in the Labrador and Irminger seas. A number of floats are grounded on the Icelandic slope east and west of the Kolbeinsey Ridge due to upslope currents, which create a rim of cold water along the slope.

Entrainment of dense water into the North Icelandic Jet, a feature on the northern Iceland slope identified by Våge et al. (2011) and defined as a current connecting the Iceland Sea east of the Kolbeinsey Ridge to the Denmark Strait sill, was one of the specific interests of this study. In this experiment, the floats did not observe the North Icelandic Jet. The tracks directed towards the sill seen on the Iceland shelf west of the Kolbeinsey Ridge are from floats that separated from the East Greenland Current, indicating at least a strong contribution from the East Greenland Current to the North Icelandic Jet. There are two possible reasons why the North Icelandic Jet pathway around the Kolbeinsey Ridge was not observed in this experiment. Firstly, even though we deployed floats specifically in the region of the North Icelandic Jet, the total number of floats is relatively low. A follow-on study, comparing these floats to simulated floats in a regional model, will investigate track sensitivity to sample size, deployment location, and depth. Secondly, the atmospheric forcing conditions during the experiment may have been less favorable for a North Icelandic Jet pathway. A time series of ERA Interim wind stress curl averaged over this region (Figure) shows that the wind stress curl was strong during the 2013–2015 float experiment period. This would favor a strong connection with the EGC rather than a strong westward North Icelandic Jet (Köhl 2010). Wind stress conditions were more favorable for a strong North Icelandic Jet in 2001 and 2002 (the years described by Jonsson and Valdimarsson 2004) and 2008 and 2009 (Våge et al. 2011).
During the next phase of the project we will use high-resolution model data to further investigate the RAFOS results to sensitivity to deployment parameters and numbers as well as variability in atmospheric conditions.

**Bibliography**


**Figure:** Time series of wind stress curl over the area around Iceland (60°N, 40°W; 72°N, 10°W; 60°N, 10°W) positively correlated with overflow transport in the study by Köhl et al. (2007). The daily wind stress curl over the whole record is drawn in light gray and over the RAFOS experiment period in red. The mean seasonal cycle is drawn in dark grey and annual average values (from June 1 to May 31) are drawn with the thick blue line. The dashed horizontal line indicates the overall mean value of the wind stress curl.
This project seeks to improve understanding of the relation between AMOC variability and surface climate. Our first step was to diagnose predictable surface patterns associated with AMOC. To this end, we identified the most predictable patterns of global SST in coupled atmosphere-ocean models with and without interactive ocean circulations (i.e., the latter models represent the ocean by a 50 m deep slab mixed layer with no interactive currents). The most predictable patterns were very similar in the two types of models. Furthermore, these patterns can be predicted skillfully on multiyear timescales in observational data using empirical models trained on simulations from either climate model. These results suggest that interactive AMOC is not essential for the spatial structure of multiyear predictability. However, the timescale of predictability is sensitive to whether the model supports interactive ocean circulations or not. These results have been published in Srivastava and DelSole (2017).

Our second activity was to reconstruct the AMOC based on North Atlantic SST. To test the proposed method, a training sample was drawn from a 500-year preindustrial control simulation from CMIP5, which permits a focus on internal variability without contamination from anthropogenic climate change. A novel aspect of the method is that it is based on Laplacian eigenvectors rather than EOFs. These eigenvectors are an orthogonal set of patterns that span the North Atlantic and are ordered by a measure of length scale. The truncation point effectively controls the spatial scales that are filtered out. The cross-validated skill of the AMOC reconstruction, based on the simultaneous North Atlantic SST in the same model, shown in the figure a, reveals that the skill of the reconstruction tends to improve as more small-scale structures (i.e., more Laplacian eigenvectors) are included. However, if the regression derived from one model is used to reconstruct the AMOC in another model, then the skill degrades as more small-scale structure is included (see Figure b as an example). This result suggests that the small-scale structure that is important in reconstructing AMOC in a particular model is not robust across models. The most robust reconstructions are based on one Laplacian eigenvector, which corresponds to the area averaged North Atlantic SST (effectively the AMO index). Skill can be improved further by adding another predictor lagged by five years, resulting in a two-parameter reconstruction model. A single, multimodel, reconstruction equation was derived and applied to each model separately. The results are shown in Figure c. Importantly, the correlation skill is nearly identical to the skill of a reconstruction model in which the parameters are optimized for each model separately. The fact that a single equation can produce nearly optimal reconstructions in different CMIP5 models provides a promising basis for reconstructing the AMOC from observational data.
**Bibliography**


**Figure:** (a) Cross validated skill of reconstructing the AMOC index in a CMIP5 model using the simultaneous North Atlantic SST in that same model (no time lag), as a function of the number of Laplacian eigenvectors in the regression model. Cross validated skill is based on leaving 10% of the data out and equals one minus the normalized mean square error. (b) Correlation skill of an AMOC reconstruction equation trained on CNRM-CM5 simulations and applied to other CMIP5 models. (c) The AMOC index in a CMIP5 model (thick colored curve) and its reconstruction (black thin curve) based on a single 2-parameter equation using North Atlantic SST as predictors. The correlation between the two AMOC indices is indicated at the end of the time series. The maximum streamfunction at 40°N in the North Atlantic was used as an index of the AMOC, and the Atlantic SST between the equator and 60°N was used for the North Atlantic SST. A five-year running mean was applied to all time series.
The objective of this grant is to categorize the sources of interannual variability in the North Atlantic. We consider variability types differentiated by their origins: locally forced, locally intrinsic, non-locally forced, or non-locally intrinsic. Locally forced refers to that variability that is generated by the regional atmospheric forcing of the North Atlantic, while locally intrinsic refers to that interannual variability arising from processes internal to the North Atlantic. The adjective nonlocal refers to the impact of northern and southern boundary condition variability on the interior North Atlantic. Our strategy is to conduct ensembles of North Atlantic simulations from 20°S to 55°N subject to open boundary conditions on the north, south, and Strait of Gibraltar and atmospheric exchanges of buoyancy and momentum. We consider cases of climatological forcing versus interannually variable forcing on the various boundaries using ensembles to isolate the forced results from the intrinsic.

Recent actions include applying for and receiving computing resources at the NSF Wyoming site. We have completed benchmarking of our configurations on both Cheyenne and Yellowstone. All required boundary and atmospheric data have been obtained from our colleagues in Grenoble, France, and needed preprocessing has been performed. Our ensembles are generated using a series of independent initial conditions. The procedure for generating these is to harvest a set of model states from the first month of a run forced by 1963 atmospheric data and 1963 model boundary conditions. These were then used as new January 1 initial conditions for an annual run under 1963 conditions. The model state at January 1, 1964 from each of these runs was then extracted from the runs and used as our ensemble collection of initial states. All 12 of these are now available.

We presented initial results of our experimentation on model drift under climatological and fully forced settings at the recent AMOC meeting in Santa Fe. We found that models forced by climatological winds and specified atmospheric temperatures often maintain relatively accurate sea surface conditions by relying on the specified temperatures. In contrast, full variability in the winds mixes heat more effectively into the ocean.

We anticipate the completion of one full 55-year long ensemble run by the end of the calendar year, and that we will be roughly 50% complete with a second ensemble.

Our ensemble generation is currently ongoing. The figure shows measures of the AMOC variability in our ensemble, which as of now is 10 years in duration for all 12 ensemble members. Each member receives full atmospheric forcing and employs fully variable north, south, and Gibraltar boundary conditions.
Figure: The background colored shading represents the ensemble mean, time averaged AMOC. It is dominated by northward-directed transport in the upper 2500 m and southward transport below. The total overturning strength is 25 Sv, broadly in line with ocean GCMs in general. The green contours are of the rms variability of the ensemble mean AMOC. Two centers of activity are found: one in the equatorial zone and one at 35°N, roughly at the latitude of Gulf Stream separation from Cape Hatteras. The equatorial region is far more energetic, with amplitudes up to 30 Sv. This variability is very high frequency; temporally averaging over timescales of a month reduces its amplitude by an order of magnitude. The Gulf Stream zone variability is on the order of a few Sv and reflects fluctuations in the path of the separated Gulf Stream. The black contours indicate the rms variability of the time mean AMOC as computed by each ensemble member. The amplitude of this variability is a less than 1 Sv and is centered almost singularly on the Gulf Stream region. Thus we infer that our ensemble members are yielding independent realizations of the chaotic mesoscale field, as we hoped, while still robustly reproducing large-scale general circulation features.

State of the Climate: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean

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This project supports the development of a methodology to estimate heat transport variability using data collected along two high density XBT transects operated by NOAA’s Atlantic Oceanographic and Meteorological Laboratory, satellite data (altimeter and scatterometer), wind products from the National Center for Environmental Prediction reanalysis, and products from general circulation models. Quarterly reports estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic are posted on the AOML website. While continued delivery of quarterly estimates of heat transport is the ultimate output
of this project, efforts are continually underway to improve these heat transport estimates and provide uncertainty estimates.

Recent results
Estimates of the heat transport across the North and South Atlantic continue to be posted on the AOML website, typically within two months of the completion of any given cruise. With the increase of Argo data, an updated T/S relationship has been developed for a better estimate salinity to decrease errors in the MHT estimates. T/S relationship developed for the South Atlantic has been updated with more available data and extended to the North Atlantic, and the MHT estimates from XBTs will be recalculated.

This year the MHT in the South Atlantic was highlighted in four publications:
• Baringer et al. (2017) extended this time series through 2016. Different from the decreasing trends of the MHT observed at 26°N and 41°N, MHT at 35°S from XBTs does not show a statistically significant trend.
• Near real-time MOC and MHT are estimated in the South Atlantic at four different latitudes between 20°S and 35°S on monthly basis using the methodology developed by Dong et al. (2015) through a combination of the satellite and in situ measurements. Results of the 25-year time series of MOC and MHT are posted on AOML website.
• The 25-year MOC time series mentioned above and SST are found highly correlated, which allowed us to extend the MOC time series back to 1870 using SST reanalysis products (Lopez et al. 2017).

In additional, the project PIs participated in a number of other studies related to MOC and MHT, including a study of the deep western boundary current transport at 35°S (at the latitude of AX18) and a study on the impact of improved thermistor calibration on the Expendable Bathythermograph profile data, which will lead to improved estimates of the MOC and MHT using XBT measurements.

Online data
XBT data: http://www.aoml.noaa.gov/phod/hdenxbt/index.php
MOC and MHT time series: http://www.aoml.noaa.gov/phod/samoc_altimetry/data_all.php

Bibliography


### Interannual-to-Decadal Variability of the SAMOC

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This project aims to better understand the SAMOC variability and to explore the impact of mesoscale eddies on SAMOC variability on interannual-to-decadal timescales. We are applying a combination of analyses of CMIP5 models and ocean model experiments to study decadal variability of the SAMOC in CMIP5 models. We explore the role of mesoscale eddies on decadal variability of the SAMOC and aim to quantify the relationship between the Southern Hemisphere westerlies and the SAMOC.

The importance of MOC derives from its role in transporting oceanic properties, in particular the oceanic heat. The conventional view is that the MOC and the associated MHT are largely modulated by deep convection activity in the high-latitude sinking regions in the North Atlantic. However, recent studies have suggested the possibility of the southern origin of the Atlantic MHT anomalies. These studies have used general circulation models to demonstrate co-variability between the SAMOC and the Southern Hemisphere westerlies at interannual to longer timescales. However, it has been pointed out that the sensitivity of the SAMOC to the changes in the Southern Hemisphere westerlies depends critically on the representation of mesoscale eddies in those models. Indeed, in the South Atlantic, eddy heat transport contributes significantly to the MHT and accounts for a considerable portion of the MHT variance. The observation-based estimates of MHT in the South Atlantic have a wide range of values, which, to some extent, is due to the misrepresentation of the eddy heat transport. Therefore, understanding the variability of the MOC/MHT in the South Atlantic on various timescales and the role of eddies in the South Atlantic are essential ingredients toward achieving decadal predictability of the Atlantic MOC and its impact on climate. Therefore, in order to better understand the variability of the MOC/MHT in the South Atlantic, we explore the impact of resolving eddies in an ocean general circulation model on interannual-to-decadal variability of the simulated SAMOC and quantify the relationship between the Southern Hemisphere westerlies and the SAMOC.
**Recent results**

We are currently analyzing outputs of the coarse and high-resolution CESM simulation from NCAR. The goal is to characterize the MOC variability in these models and to investigate the differences and similarities between the coarse and high-resolution models. Our preliminary analysis of the coarse resolution model suggests that on interannual-to-decadal timescales:

- In the South Atlantic between 8°S and 35°S, oceanic heat transport convergence dominates changes in the heat content in the region, which, in turn, forces fluxes into the atmosphere with a 5-year lead.
- The oceanic heat transport convergence in the study region is largely controlled by the transport at 8°S, the northern boundary.
- An EOF analysis of heat content reveals a dipole structure with centers located at 28°S and 13°S. This dipole structure is consistent with the dominant mode of the SST and SSH found in previous studies.

**Figure:** Time-mean eddy kinetic energy (EKE) at the ocean surface computed from the geostrophic velocity of satellite altimetry (top), non-eddy permitting model CESM1 (middle), and the eddy-resolving model CCSM4 (bottom). Units are cm$^2$ s$^{-2}$. Note that a different color scale is used for CESM1 due to its low values.
The Interannual Variability of the Brazil Current

PIs: M. Goes\textsuperscript{1,2}, S-K Lee\textsuperscript{2}, and S. Dong\textsuperscript{2}

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\textsuperscript{2} NOAA Atlantic Oceanographic and Meteorological Laboratory

The main goal of this project is to understand the variability of the Brazil Current with focus on interannual timescales. The links of the Brazil Current with large-scale features, such as the gyre variability and AMOC, extreme weather and climate events in the South Atlantic, and teleconnections with other basins, are analyzed. For this, a host of \textit{in situ}, satellite, and model data are used.

Recent results
In a recent paper (Siqueira et al. 2017), we analyze the air-sea interaction in two coupled model simulations in the BC region. These simulations feature different ocean model resolutions: one at high-resolution (HR; 0.1 deg) and the other at low resolution (LR; 1 deg). We show that the impact of the Brazil Current front and the heat carried by the BC on the air-sea interaction is crucial to simulate the interannual variability of summer (Dec–Feb) precipitation in South America.

To analyze the impact of the ocean on the summer precipitation, composites (cold and warm) are made of the western subtropical South Atlantic (WSSA) region (50°W–30°W, 34°S–25°S) SST variability, which is the large-scale region with most influence in the South American precipitation retrieved from coupled ocean-atmosphere modes of variability.

The large-scale teleconnections from the Pacific to the western South Atlantic are broadly consistent between the two simulations. However, many of the regional details, particularly associated with local air-sea interactions and the Brazil Current, are markedly different. Specifically, anomalous dry and wet areas along the coast in the ocean eddy-resolving coupled model are not linked to the large-scale atmospheric forcing but rather to anomalous SST associated with variability in the strength of the boundary currents. The dominant differences include a large reduction in convective precipitation along the subtropical shelf due to colder near-coastal SSTs and reduced turbulent heat fluxes during periods when the western South Atlantic is anomalously warm due to ENSO teleconnections. Ocean temperature sections near the coast also show large differences, with the eddy-resolving model in better agreement with observational estimates. Finally, initialized retrospective forecast experiments confirm the simulation results and suggest that sub-seasonal to seasonal predictions can be improved by including resolved ocean eddies.

The figure shows details of the cold WSSA composite. The SSTA pattern in the cold WSSA composite is not centered near the continental shelf but away from the boundary. This suggests that the SST anomalies in the cold events are unlikely to be resulting from coastal upwelling. Instead, there is in both LR and HR simulations a southward stream of warmer SSTA along the BC path (Figure a, b). This warm stream off the Brazilian coast is much more pronounced in HR, consistent with a stronger and narrower Brazil Current relative to the LR model. In HR, this increased front across the Brazil Current is responsible for a \~20\% increase in convective
precipitation anomalies parallel to the coast when compared to LR (Figure d, f). This mode is consistent with a clockwise flux circulation favoring a northern position of the South Atlantic convergence zone.

The figure also suggests that during the cold WSSA events, a stronger Brazil Current front along the coast in the HR model is associated with stronger turbulent heat release into the atmosphere favoring a widening of the marine atmospheric boundary layer. The changes in the atmosphere may therefore be associated with the vertical mixing (VMM) air-sea coupling mechanism.

**Bibliography**

**Figure:** Cold WSSA composite of SSTA (shaded) and 850hPa water vapor transport (arrows) (a) LR and (b) HR model with hatched area indicating convergence of the water vapor transport; composite of convective precipitation rate of (c) LR and (d) HR model; composite of convective precipitation contribution (%) to total precipitation of (e) LR and (f) HR model. Stippled areas denote regions significant at the 95% level, based on bootstrap confidence intervals estimated by generation of 1000 random composite maps for the DJF period. The box in panel (a) represents the WSSA region.
Assessment of the Meridional Overturning Circulation and Meridional Heat Transport and their Meridional Variability in the South Atlantic Ocean

PIs: G. Goni, and S. Dong
NOAA Atlantic Oceanographic and Meteorological Laboratory

The goal of this project is to investigate latitudinal and temporal changes of the MOC and MHT in the South Atlantic Ocean using altimetry observations from joint satellite missions as the primary data in concert with other ancillary in situ and satellite datasets (XBTs, Argo, satellite winds). The new methodology developed to obtain the MOC and MHT time series during the altimeter period were described in Dong et al. (2015).

Recent results
Satellite altimetry and in situ data are used to estimate the MOC and MHT in the South Atlantic since 1993 in the region between 20°S and 35°S. Analysis of the 24-year time series of MOC and MHT indicates that the interannual variations in the MOC at different latitudes are statistically correlated, with MOC at 35°S leading that at 20°S by about 20 months. Results also show that the dominance of the geostrophic (density-driven) and Ekman (wind-driven) transports on the interannual variations in the MOC and MHT varies with time and latitude. The time series indicate that at 20°S the Ekman component plays a larger role than the density-driven component. On the other hand, at 35°S the geostrophic component dominates over most of study period, except during 2007–2012 when the Ekman component dominates. Further analysis shows that, consistent with results in other regions, the oceanic heat convergence drives the heat content changes in the study region on interannual time scale, which in turn forces heat fluxes into the atmosphere. The MHT at both 20°S and 35°S appear to contribute equally to the heat convergence in the region. An important key result obtained is that the MOC exhibits positive anomalies since 2013. Time series of the MOC and MHT in the South Atlantic can be found at: http://www.aoml.noaa.gov/phod/samoc_altimetry/data_all.php.

The 24-year MOC time series mentioned above and SST are found highly correlated, which allowed us to extend the MOC time series back to 1870 using SST reanalysis products (Lopez et al. 2017).

Bibliography
The XBT Network Program

Pls: G. Goni, M. Baringer, S. Dong
NOAA Atlantic Oceanographic and Meteorological Laboratory

The XBT Network is an international effort that supports the design, implementation, maintenance, evaluation, and data acquisition, transmission, and distribution of a network of eXpendable BathyThermographs (XBTs) that obtains temperature profiles along fixed predetermined transects. Deployments are carried out from cargo vessels, cruise ships, and research vessels. Transects are repeated several times per year to measure the water temperature from the sea surface to a maximum depth of usually 850m. The XBT network currently in place has been recommended by the international scientific community during the OceanObs99 and OceanObs09 meetings, and during the five XBT science meetings that have already taken place since 2011. The global XBT network is a truly international effort. The countries that provided the largest contributions to the AOML XBT operations (including deployments, data processing, data
quality control, and data analysis) during Fiscal Year 2017 were the Australia, France, South Africa, Brazil, Italy, and Argentina. In average, approximately 20,000 XBTs are deployed per year globally, of which NOAA/AOML is involved in some aspect of the logistics, operations, data processing, etc., of about 80% of them. NOAA/AOML leads or co-leads with its international partners the implementation and operations of 12 Atlantic Ocean transects. In addition, the XBT network is supported by scientists from several countries, in the analysis and assessments of XBT biases to reduce errors in the temperature profiles.

XBT-derived temperature profiles represent between 10% and 15% of all global, non-mooring, temperature profiles. The main contribution of the XBT network is to provide temperature measurements to:

- Assess meridional heat transport in all ocean basins,
- Monitor changes of key surface and subsurface currents,
- Help initialize and validate climate and weather numerical forecast models, and
- Supplement other observational platforms to assess the variability of the global upper ocean heat content.

The main focus of the XBT network is to maintain the High Density XBT transects. The strength of the XBT data set currently lies in its length and on its ability to estimate heat and mass transports across entire ocean sections and at key choke points, such as Drake Passage, Indonesian Throughflow, the Antarctic Circumpolar Current south of Africa, and monitoring key ocean currents. The scientific objectives for this mode of deployment are summarized below:

- Measure the seasonal and interannual fluctuations in the transport of mass, heat, and freshwater across transects which define large enclosed ocean areas and investigate their links to climate indices.
- Determine the long-term mean, annual cycle and interannual fluctuations of temperature, geostrophic velocity, and large-scale ocean circulation in the top 800 m of the ocean. In some regions, XBTs reaching 800 m cannot depict the complete vertical structure of fine but intense oceanic jets and a combined approach in terms of High Density sampling and deeper profiling float measurements is necessary.
- Obtain long time-series of temperature profiles at approximately repeated locations in order to unambiguously separate temporal from spatial variability.
- Determine the space-time statistics of variability of the temperature and geostrophic shear fields.
- Provide appropriate in situ data (together with Argo profiling floats, tropical moorings, air-sea flux measurements, sea level etc.) for testing ocean and ocean-atmosphere models.
- Determine the synergy between XBT transects, satellite altimetry, Argo floats, and models of the general circulation.
- Identify permanent boundary currents and fronts, and describe their persistence and recurrence and their relation to large-scale transports.
- Estimate the significance of baroclinic eddy heat fluxes.

Recent results
Two XBT transects are dedicated to monitor the AMOC, AX07 in the North Atlantic along ~30N, and AX18 in the South Atlantic along ~34.5S. Estimates of the heat transport from these two transects
continue to be posted on the AOML website, typically within two months of the completion of any given cruise. This year the MHT in the South Atlantic was highlighted in two publications:

• Baringer et al. (2017) extended this time series through 2016. Different from the decreasing trends of the MHT observed at 26°N and 41°N, MHT at 35°S from XBTs does not show a statistically significant trend.
• Near real-time MOC and MHT are estimated in the South Atlantic at four different latitudes between 20S and 35S on monthly basis using the methodology developed by Dong et al. (2015) through a combination of the satellite and in situ measurements. Results of the 25-year time series of MOC and MHT are posted on AOML web site at http://www.aoml.noaa.gov/phod/samoc_altimetry/data_all.php.
• The 25-year MOC time series mentioned above and SST are found highly correlated, which allowed us to extend the MOC time series back to 1870 using SST reanalysis products (Lopez et al. 2017).

Online data
XBT data: http://www.aoml.noaa.gov/phod/hdenxbt/index.php

Bibliography
The aim of our project is to investigate the year-long transports and variability in the upstream sources of the Denmark Strait overflow. The Denmark Strait overflow is a major contributor to the return flow of dense water from the Nordic Seas to the sub-tropics, supplying the densest half of the water in the DWBC. However, there remain large open questions relating to the upstream sources of the overflow water and how these regions might be influenced under a changing climate. We are investigating these questions using hydrographic and velocity data from a composite array of 12 moorings that spanned the width of the Denmark Strait, approximately 200 km upstream of the sill, from September 2011 to August 2012. Our major goal this year has been to understand the large synoptic-scale variability in the North Icelandic Jet, a major pathway of overflow water into the Strait.

Recent Results

• Significant sub-weekly variability exists in the North Icelandic Jet and separated East Greenland Current on the Iceland slope. This signal dominates the velocity signatures on the Iceland slope and has maximum energy at a period of four days. This period matches the variability seen downstream at the sill suggesting some connectivity. This has motivated our further understanding of the underlying synoptic dynamics in this upstream current system.

• The four-day variability in the North Icelandic Jet is consistent with the existence of topographic Rossby Waves on the Iceland slope. Flow variance ellipses are obliquely angled to the mean current vectors, the wave phase propagates downslope, and the measured parameters of the wave match those predicted by the topographic Rossby Wave dispersion relationship (Figure).

• We show that the group velocity (and energy propagation) is directly upslope at the array site indicating an offshore source of energy (Figure). We corroborate this through an inverse wave-tracing model, which shows neither an upstream or downstream deflection of wave paths. The source of the energy is local and not propagating upstream from or downstream to the sill.

• We hypothesize two mechanisms for the energy creation. The first is a meandering separated East Greenland Current on the Iceland slope; the period of meandering is similar to that seen in the North Icelandic Jet. The second is intermittent aspiration into the sill (seen in our previous study), which would necessarily drive flow across isobaths. Regardless, the similarities between the signal periods in the North Icelandic Jet and at the sill suggest that these signals are linked, even if there is a secondary mechanism that mediates the connection. This is the subject of our ongoing research.

Bibliography


**Figure:** Aspects of the flow measured by the moorings (black circles) in the Denmark Strait Array on in the Iceland Slope. The thin vectors indicate the mean velocity averaged from 100 m to the depth of the ADCP at each mooring. Also shown are the 8-day high-passed current ellipses for the same depth range. The thick black arrow (C_p) denotes the direction of TRW phase propagation averaged over KGA 2-4 (for which the ellipses are obliquely aligned to the mean current and TRW theory holds), which is offshore and downslope. The dashed black arrow shows the direction of TRW group velocity (C_g), which is directed almost exactly upslope indicating an offshore energy source. All vectors and current ellipses are drawn to the same scale as indicated. The long black line is the mean downslope direction averaged between KGA 2-4. The bathymetry is from IBCAO v3.
Diagnosing Overturning and Water Mass Transformation in the Labrador Sea From Argo Floats

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In this study, we use Argo floats to quantify Labrador Sea overturning and its variability on seasonal timescales. Floats offer some advantages over previous observations in the Labrador Sea because, although their sampling is spatially irregular, they have collected observations in all seasons, allowing for an examination of the seasonal signal of the overturning. Seasonal composite geostrophic velocity sections are assembled across the mouth of the Labrador Sea from float potential density profiles and trajectories at 1000 m. These sections are used to calculate the seasonal overturning circulation in depth and density space, as well as the horizontal circulation; they also provide insight into the mechanisms driving the seasonal overturning.

- We find a substantial seasonal cycle in the Labrador Sea overturning; in depth space it doubles throughout the course of the year and in density space it triples. The overturning is largest in spring (3.9 ± 0.7 Sv in density space), shrinks through summer, and reaches a minimum in winter (1.2 ± 1 Sv in density space). The error bars for each seasonal estimate are calculated by averaging 10000 bootstrapped seasonal overturning estimates. In depth space, the overturning varies from a maximum of 1.2 ± 0.6 Sv at a depth of 900 m in spring to a minimum of 0.6 ± 0.7 Sv in winter. The large spring overturning is associated with the export of recently formed Labrador Sea Water in the Labrador Current.

- Eleven late spring/early summer hydrographic sections across the AR7W line support the seasonal overturning signal identified by Argo. The similarity in the overturning estimates from these two data sources (they are within 0.15 and 0.4 Sv in depth and density space, respectively) suggests that float observations can capture the majority of the overturning.

- The mean overturning is approximately 0.9 ± 0.5 Sv in depth space and 2.5 ± 0.75 Sv in density space.

The large seasonality in the overturning, particularly for density, implies that it might be difficult to accurately estimate the overturning’s mean strength, let alone assess its interannual variability, using a handful of synoptic sections. As the overturning is not particularly large and interannual variations seem likely to be small, sustained and thorough observations that resolve the seasonal signal will likely be needed to monitor long-term changes in the overturning.

\textit{Bibliography}
Amplified North Atlantic warming in the late Pliocene by changes in Arctic gateways

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Under previous reconstructions of late Pliocene boundary conditions, climate models have failed to reproduce the warm SSTs reconstructed in the North Atlantic. Using a reconstruction of mid-Piacenzian paleogeography that has the Bering Strait and Canadian Arctic Archipelago Straits closed, however, improves the simulation of the proxy-indicated warm SSTs in the North Atlantic in the Community Climate System Model. We find that the closure of these small Arctic gateways strengthens the AMOC, by inhibiting freshwater transport from the Pacific to the Arctic Ocean and from the Arctic Ocean to the Labrador Sea, leading to warmer SSTs in the North Atlantic. This indicates that the state of the Arctic gateways may influence the sensitivity of the North Atlantic climate in complex ways, and better understanding of the state of these Arctic gateways for past time periods is needed.
**Bibliography**


**Figure:** Comparison of AMOC in Pliocene simulations. (a) Annual-mean AMOC (Sv) from PlioMIP1 simulation. Positive and negative contours indicate clockwise and counterclockwise circulation, respectively. (b–d) Change in the AMOC as compared to the PlioMIP1 simulation for the closed Bering Strait, closed Canadian Arctic Archipelago, and closed Bering Strait+Canadian Arctic Archipelago experiments, respectively. Top numbers in color bar are used by (a), and bottom numbers are used by (b–d).

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**Internally Generated and Externally Forced Multidecadal Oceanic Modes and Their Influence on the Summer Rainfall over East Asia**

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Interdecadal oceanic variability can be generated from both internal and external processes, and variability can significantly modulate climate on global and regional scales, including the warming slowdown in the early 21st century and rainfall in East Asia. By analyzing simulations from a unique CESM-LE project, it is shown that the IPO is primarily an internally generated oceanic...
variability, while the AMO may be an oceanic variability generated by internal oceanic processes (e.g., AMOC) and modulated by external forcing in the 20th century. Although the observed relationship between IPO and the Yangtze-Huaihe River valley (YHRV) summer rainfall in China is well simulated in both the preindustrial control and the 20th century ensemble simulation, none of the 20th century ensemble members can reproduce the observed time evolution of both the IPO and YHRV rainfall because of the unpredictable nature of IPO on multidecadal timescales. On the other hand, although CESM-LE cannot reproduce the observed relationship between the AMO and Huanghe River valley (HRV) summer rainfall of China in the preindustrial control simulation, this relationship in the 20th century simulations is well reproduced, and the chance of reproducing the observed time evolution of both AMO and HRV rainfall is about 30%, indicating the important role of the interaction between the internal processes and the external forcing to realistically simulate the AMO and HRV rainfall.

**Bibliography**

**Figure:** The wavelet power spectrum of the (a) AMO and (b) AMOC in the control run. The thick black contours designate the 95% confidence level against red noise. The years from 400 to 2000 show the model time.
Measuring interannual variability of the AMOC and meridional ocean heat transport at 26.5°N: The RAPID-MOCHA Array

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The objective of this program is to continuously monitor the strength and structure of the AMOC and MHT at 26.5°N using a basin-wide observing system. As of March 2017, we have completed 13 years of observations. Funding for the present array will continue through at least 2020.

**Recent results**

An update of the 26.5°N AMOC time series has been recently posted here, extending the dataset through March 2017 (Figure). The most significant interannual event observed thus far in the time series was the pronounced AMOC downturn in 2009–2010 where the AMOC reached annual mean values of 14.6 and 15.0 Sv, respectively, and maintained values of less than 10 Sv for a four month period during winter 2010. The 0.6 Sv per yr decline over the period from 2007–2011 was almost ten times larger than the rate predicted by the IPCC (Smeed et al. 2014) and is believed to represent primarily a wind-forced response over the subtropical North Atlantic (Zhao and Johns 2014; Zhao 2017; Moat et al. 2016). The updated time series suggests that the AMOC has not reduced further during 2012–2017 but has continued to occupy a weaker circulation state relative to the first years of observations. This change of AMOC state is found to be concurrent with other changes in the North Atlantic, such as a broadening of the Gulf Stream, evidenced by a change in the currents observed by satellite altimetry and by altered patterns of OHC and SST that resemble the pattern of response to a declining AMOC predicted by coupled climate models (Smeed et al. 2017). Concurrent changes in air-sea fluxes also suggest that the changes in ocean heat transport and SST have altered the pattern of ocean-atmosphere heat exchange over the North Atlantic.

The MHT at 26.5°N continues to show a high correlation with the AMOC strength (r=0.94) and showed a decrease from 1.33±0.05 PW for 2004–2008 to 1.17±0.07 PW for 2011–2015. Most of the reduction in the AMOC (and MHT) can be attributed to changes in the geostrophic (non-Ekman) circulation, linked primarily to an increase in the southward upper ocean transport across the ocean interior. Observations of OHC from Argo data show that the North Atlantic OHC reached a decadal peak in about 2007 and has since declined, consistent with the lower recent AMOC and MHT values recorded by the 26.5°N array.

Looking forward toward possible optimization of the RAPID-MOCHA array beyond 2020, McCarthy et al. (2017) explored alternative array configurations within the context of the existing 26.5°N dataset as well as within a suite of Hadley Centre and CMIP5 models. Results suggest that much of the seasonal-to-interannual AMOC variability observed since 2004 could be reproduced by a reduced mid-ocean array with single tall mooring on the western boundary and a single mid-depth mooring on the eastern boundary. However, testing of the array within the coupled climate
simulations showed that deep, basin-wide measurements similar to those available from the current array are essential to correctly capture future long-term changes of the AMOC.

**Data are available online:**
MOC data: http://www.noc.soton.ac.uk/rapidmoc/
Heat transport data: http://www.rsmas.miami.edu/users/mocha/

**Bibliography**

**Figure:** Time series of the AMOC at 26.5°N (black), and the transport components of the "upper branch" of the AMOC (Gulf Stream (blue); Ekman (green); and upper mid-ocean (red)). High-frequency data are 10-day averages and smooth curves represent 90-day lowpass filtered values. Annual mean values for the AMOC during each year are shown in shaded boxes.
Decadal Variability of Interacting Climate Subsystems in the Northern Hemisphere

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In this project, we study the Northern Hemisphere climate's decadal variability using data output from a suite of state-of-the-art coupled climate models. Our primary approach is to examine networks of climate indices that generally represent coupled climate subsystems. We analyzed the CMIP5 multi-model simulations of the 20th century climate change, as well as the simulations from the CESM-LE (Kay et al. 2015), to isolate forced and internal components of variability in the climate index network considered. The model derived forced signals were also used to estimate the internal component of climate variability in the observed indices. We then applied advanced statistical methods to compare the spatiotemporal structure of the observed and simulated internal variability. These results point to important differences between the observed and simulated interannual-to-decadal climate variations, which, among other things, shall help inform the Earth system model development efforts.

Recent results
We employed a newly developed semi-empirical methodology (Kravtsov and Callicutt 2017; Kravtsov 2017) to estimate internal variability in observations and CMIP5 models for a number of SST and SLP climate indices, namely: AMO and Pacific Multidecadal Oscillation (PMO) indices representing SST averages over the Atlantic and Pacific Oceans, respectively, the Northern Hemisphere Multidecadal Oscillation (NMO) index for the Northern Hemisphere mean surface temperature, as well as the NAO index and its analog over the Pacific-Aleutian Low-Pressure Index (ALPI), both based on SLP fields.

We then used multi-channel singular spectrum analysis (M-SSA) to study and compare spatiotemporal structure of the internal decadal variability in observations and models (Figure). The observed internal variability exhibits a pronounced hemispheric multidecadal mode with a distinctive spatiotemporal signature, which is altogether absent in model simulations. This single mode explains a major fraction of model-data differences over the entire climate-index network considered; it may reflect either biases in the models' forced response or models' lack of requisite internal dynamics, or a combination of both.

Similar large differences between observations and CMIP5 simulation were detected in the analysis of ENSO dynamics (Jajcay et al. 2017).

We strongly believe that model development activities should strive to alleviate the present large discrepancies between the observed and simulated interannual-to-multidecadal climate variability, as these discrepancies hinder our fundamental understanding of the observed climate change.
Bibliography

**Figure:** The M-SSA analysis of the observed and simulated internal variability in the AMO−PMO−NMO−NAO−ALPI climate-index network. Left column: the results of M-SSA analysis using the embedding dimension of M=20; right column: the same for M=40. Upper row: M-SSA spectra. The spectra based on the observed data (ensemble-mean variances and their ±1 STD spread) are in blue, and the spectra based on CMIP5 model historical and control simulations are in red and black, respectively. The green error-bar plot (and lower black error-bar plot) represent the variances of the time series obtained by projecting the trajectory matrices from historical (or control) model simulations onto the ST-EOFs of the observed trajectory matrix. The spectra of the observed internal variability inferred using one-, two-, and three-factor scaling methods of Frankcombe et al. (2015) are shown by x-symbols, circles, and diamonds, respectively. Bottom row: Reconstructed components (RCs) corresponding to the leading M-SSA pair of the observed data. The NAO and ALPI RCs were multiplied by −1. For the purposes of better visualization, the RCs corresponding to different indices (channels) were vertically stacked by adding the constant offsets of +1, +2, +3, and +4 to the RCs for AMO, −NAO, PMO and NMO indices, respectively. Comments: (i) Model-data differences are dominated by the leading M-SSA pair, whose observed spatiotemporal structure is absent from models (upper row). (ii) This mode, in observations, is characterized by a pronounced coherent multidecadal signal across the entire climate network considered (bottom row). Adapted from Kravtsov (2017).
The southward returning pathways of the AMOC and their impacts on global sea surface temperature

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A recent study showed that climate models with weaker AMOC are associated with colder upper ocean temperature biases in the North Atlantic. However, in many of the climate models that participate the CMIP5, the amplitudes of the AMOC agree very well with or are even larger than the observed value of about 18 Sv at 26.5°N, but they still show cold upper ocean temperature biases in the North Atlantic. This suggests that the AMOC strength may not be the only factor that determines the meridional ocean heat transport. A common symptom in these models is that the returning flow of the AMOC at depth is too shallow. A shallow returning flow would carry excessive heat southward; thus the net northward heat transport by the AMOC would be weaker than the observed. We propose to perform quantitative analysis to test the above hypothesis using available observations, CMIP5 model outputs, and ocean and sea ice model experiments.

Recent results
In a recent article, Lee et al. (2017) reported that the meridional ocean heat transport in the South Atlantic sector is closely linked to the sea ice trends over the Weddell Sea. The poleward shifting Southern Hemispheric westerlies in the South Atlantic sector strengthened the northern branch of the Weddell Gyre, which in turn increased the meridional thermal gradient across it as constrained by the thermal wind balance. As summarized in the Figure, ocean heat budget analysis further suggests that the strengthened northern branch of the Weddell Gyre acted as a barrier against the poleward ocean heat transport and, thus, produced anomalous heat divergence within the Weddell Gyre and anomalous heat convergence north of the gyre. The associated cooling within the Weddell Gyre and the warming north of the gyre contributed to the expansion of sea ice in warm seasons and the retreat in cold seasons, respectively. This work was selected as Journal of Geophysical Research Editors’ Highlight.

In a newly accepted paper, Goes and colleagues (Murphy et al. 2017) explored the role of dust-climate feedbacks and increased North Atlantic freshwater discharge on the AMOC during Heinrich events. Model simulations show that including both freshwater and dust forcing results in a cooling of the subtropical North Atlantic more comparable to proxy records than with freshwater forcing alone. Enhanced Saharan dust loading during the most recent Heidrich stadial can extend the geographical range of cooling by locally influencing the radiative balance, increasing sea ice, and also though ocean dynamical feedbacks by destabilizing the AMOC. This study concludes that dust-climate feedbacks may provide an amplification to Heinrich cooling by further weakening AMOC and increasing North Atlantic sea ice coverage.
Bibliography

Figure: Sketch of the physical mechanisms that link the meridional ocean heat transport and the Antarctic sea ice trends in the South Atlantic sector.

Understanding mechanisms of projected 21st century ocean warming around Greenland

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Over the past year, the project team has pursued several analyses, including: i) diagnosis of mechanisms underlying observed decadal changes in large-scale North Atlantic heat content; ii) comparison of these mechanisms to those driving warming (and model spread) in centennial-timescale climate model projections; iii) assessment of the role of Greenland ice sheet mass balance on the large-scale ocean circulation in the near-Greenland coastal seas; and iv) examination of the relationship between past and future North Atlantic heat content, AMOC, and coastal sea level. Mechanistic pathways have been assessed using observations (e.g., tide gauge
and OHC datasets), free-running climate models, and data-constrained ocean state estimates. Research products have been disseminated as publications (below) and related conference presentations, including the 2017 US AMOC meeting. New results will be presented at the upcoming meetings and conferences.

Recent results
The responses of AMOC, SST, and dynamic sea level in the North Atlantic to more realistic estimates of the 21st century melting of the Greenland Ice Sheet have been investigated systematically using the GFDL ESM2Mb model (Beadling et al. 2016). The results have been compared to other climate models in the AMOCMIP project (Bakker et al. 2016; see figure). Little et al. (2017) used the Community Earth System Model Large Ensemble to assess how past and future coastal sea level changes are related to local winds and large-scale ocean circulation. The study demonstrates that observation-based interpretations, highlighting the role of winds, are not inconsistent with the dominance of AMOC-associated changes in the 21st century; identifies the coastal regions that are well- and less well-represented in current generation climate models; and suggests the time periods over which coastal sea level may be used as a proxy for the large-scale ocean circulation.

Piecuch et al. (2017) used the ECCO state estimate to show that the subpolar North Atlantic OHC trend reversal from 1994–2004 to 2005–2015 arose largely from variable heat transports by the ocean's mid-latitude horizontal gyre circulation that are strongly correlated with the local wind field.

A manuscript in preparation identifies three independent “modes” that explain ~70% of the inter-model variance in centennial-timescale upper ocean warming near Greenland across the CMIP5 ensemble. Two of these modes are strongly related to inter-model differences in surface salinity. Ongoing numerical simulations, with complete heat and salt budgets, will help evaluate inferences about mechanisms underlying these modes of ocean warming and sea level change.

Bibliography
**Figure:** Simulated AMOC projections as part of AMOCMIP project. Results of eight GCMs are shown for the historical period combined with (left column) RCP4.5 and (right column) RCP8.5 and for the experiments without Greenland Ice Sheet mass loss, with gGrISmelt (based on the 1971–2000 average for the individual GCMs), and with rGrISmelt (a combination of RACMO2-based historical (1971–2000) liquid runoff and observed GrIS solid ice calving rate). Results are given for AMOC strength at 26°N (below 500 m; (top row) Sv) and for (bottom row) changes (%) in the AMOC strength at 26°N relative to 2006. A 50-year running mean is applied. Depicted RAPID data are an average over all available data between 2004 and 2014 (McCarthy et al. 2015), with uncertainty bars reflecting the year-to-year variability (1σ = 2.2 Sv).
The Role of Ocean Dynamical Feedback and Air-Sea Interaction in the Climate Response to Global Warming

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This project considers global and regional climate changes due to greenhouse gas increases. Among the robust regional climate changes found in ensembles of climate model simulations, three are addressed here: a pattern of "El Nino-like" SST changes in the tropical Pacific; a minimum in the warming of SSTs in the tropical North Atlantic area which is the main development region for Atlantic tropical cyclones, accompanied by an increase in vertical wind shear in the region; and the meridional shift in the ICTZ, which has been tentatively ascribed to the slowdown of the AMOC caused by global warming.

Recent results
The uncertainty of AMOC response to CO$_2$ forcing is investigated with a particular focus on the AMOC stability bias. The AMOC change is moderate in most climate model projections under increasing CO$_2$, which is found to be possibly an artifact of common model biases that favor a stable AMOC. Observationally based freshwater budget analyses suggest that the AMOC is in an unstable regime susceptible to large changes in response to perturbations. A bias corrected NCAR CCSM3 climate model further shows that the AMOC collapses 300 years after the atmospheric CO$_2$ concentration is abruptly doubled from the 1990 level (Figure a). Compared to an uncorrected CCSM3, the AMOC collapse brings about large, markedly different climate responses: a prominent cooling over the northern North Atlantic and neighboring areas, sea ice increases over the Greenland-Iceland-Norwegian seas and to the south of Greenland, and a significant southward ITCZ shift over the tropical Atlantic (Figure b,c).

Based on observations and NCAR CESM large ensemble simulations, the relationship between ocean heat uptake and global warming hiatus has been revealed. Ocean heat uptake is observed to penetrate deep into the Atlantic and Southern oceans during the recent hiatus of global warming. Nevertheless the deep heat penetration in these two basins is not unique to the hiatus but is characteristic of anthropogenic warming and merely reflects the depth of the mean meridional overturning circulation in the basin. It has been found that heat redistribution in the upper 350 m between the Pacific and Indian oceans is closely tied to the surface warming hiatus. Particularly, the Indian Ocean shows an anomalous warming below 50 m during hiatus events due to an enhanced heat transport by the Indonesian throughflow in response to the intensified trade winds in the equatorial Pacific.

Bibliography
**Figure:** (a) Evolution of AMOC strength in the control (CTL, blue) and adjusted (ADJ, red) NCAR CCSM3 pre-industrial runs and their corresponding double CO$_2$ simulations (CTLCO$_2$, light blue; ADJCO$_2$, orange). A 10-year smoothing is applied to remove interannual variability. Long-term (after 300 years) responses of (b) surface temperature and (c) precipitation to CO$_2$ increase in the adjusted CCSM3 (the ADJCO$_2$ minus the ADJ).

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**Inter-hemispheric variability of the South and North Atlantic MOCs and its decadal modulations of global monsoon circulations and extreme weather events in the US**

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The goal of this project is to enhance our understanding of the AMOC variability, flow pathways, and its potential role in modulating climate variability and high-impact extreme weather events (e.g., heat waves, drought, and extreme precipitation) over the United States on decadal timescales. To achieve this goal, we are working on the following objectives: i) diagnose internal variability of inter-hemispheric AMOC flow pathways in observations and coupled general circulation models; ii) explore interannual variability of AMOC and its potential influence on regional climate and weather using observations and coupled model simulations; iii) explore the inter-hemispheric AMOC variability and its impact on global monsoon circulation and extreme weather events at decadal-to-multidecadal timescales from coupled model simulations. The
information gathered will be informed to the operational forecasting community to help direct future improvement in forecasting systems.

**Recent results**

We employed observational and model products as well as statistical analysis to study how the SAMOC is influenced by various teleconnections and forcing factors. Here, we show that SAMOC is strongly correlated with the leading mode of SSH variability in the South Atlantic Ocean, which displays a meridional dipole between north and south of 20°S. A significant portion (~ 45%) of the South Atlantic SSH dipole variability is remotely modulated by the IPO. Further analysis shows that anomalous tropical Pacific convection associated with the IPO forces robust stationary Rossby wave patterns, modulating the wind stress curl over the South Atlantic Ocean. A positive (negative) phase IPO increases (decreases) the westerlies over the South Atlantic, which increases (decreases) the strength of the Subtropical Gyre in the South Atlantic and thus the SAMOC (Lopez et al. 2016).

Using a combination of observational and model products as well as statistical analysis, we were able to reconstruct a century long (i.e., 1870–present) time series as a proxy of SAMOC variability based on SST. The reconstructed index is highly correlated to the observational-based SAMOC time series during the trained period (i.e., 1993–present) and provides a long historical estimate (Figure). It is shown that the IPO is the leading mode of SAMOC-SST covariability, explaining ~85% with the Atlantic Niño accounting for less than 10%. The reconstruction shows that SAMOC has recently shifted to an anomalous positive period, consistent with a recent positive shift of the IPO (Lopez et al. 2017).

We characterized the most common heat wave patterns over the US by the use of clustering of extreme events by their spatial distribution. This allowed us to identify four dominant heat wave patterns (i.e., Western, Northern Plains, Southern Plains, and Great Lakes patterns). We also show that natural variability will dominate heat wave occurrence over the Great Plains. In contrast, external forcing from climate change will dominate heat wave occurrence over the Western and Great Lakes regions, suggesting caution in attributing heat extremes to external forcing due to their regional dependence. The climate change signature on Great Plains heat waves is reduced by a projected increase of the Great Plain low-level jet and moisture transport from the Gulf of Mexico, attenuating the surface warming due to climate change. This hints at the possibility for Atlantic Ocean variability in playing a major role in US heat waves modulation (Lopez et al. 2018).

**Bibliography**


Figure: SAMOC time series obtained from altimetry (black) and those reconstructed from SST and SAMOC joint variability (color). All time series were normalized by their standard deviation. A grey box highlights the trained period.
OSNAP: Overturning in the Subpolar North Atlantic Program

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OSNAP is a US-led international program designed to provide a continuous record of the full-water column, trans-basin fluxes of heat, mass, and freshwater in the subpolar North Atlantic. The OSNAP observing system consists of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West) and the second from the southeastern tip of Greenland to Scotland (OSNAP East). The observing system also includes subsurface floats (OSNAP Floats) in order to trace the pathways of overflow waters in the basin and to assess the connectivity of currents crossing the OSNAP line. The entire OSNAP observing system (OSNAP East, OSNAP West, and OSNAP Floats) was deployed in the summer of 2014. In the summer of 2015, all moorings except those on the eastern and western slopes of Greenland were recovered and redeployed during three OSNAP cruises. Data from the full array was recovered in the summer of 2016 (and moorings reset for an additional two years), and RAFOS floats deployed in the summers of 2014 and 2015 surfaced in 2016 and 2017, respectively. The remaining floats will surface in 2018.

Recent results
The last retrieval for the first OSNAP dataset was in September of 2016, and the processing of all data was completed in late June of 2017. The MOC, MHT and MFT time series presented here are preliminary; a finalization of these time series is expected in the winter of 2018, with a manuscript submission shortly thereafter. Our estimate of the MOC across the entire OSNAP line (Figure) shows a range of 17 Sv over the 21-month period. The mean MOC is 14.79 ± 4.52 Sv; using the definition of the maximum overturning. The MHT is strongly correlated with the MOC (r= 0.88); yet the MFT is not (r=-0.21), a result that will need further investigation.

We are in the early stages of the scientific analysis of the west Greenland mooring array data. We have quantified the tides and then removed them from the time series, have identified the optimal rotated coordinate system, and are in the process of creating time series of vertical sections of hydrographic variables and along-stream/cross-stream velocities. Transports have been calculated in different density layers, revealing interesting seasonal to interannual signals, which are being investigated.
Between 2014–2017, 124 RAFOS floats were deployed for two-year missions at overflow water depths (1800-2800 m) along five transects across the deep boundary currents of the SPNA. The floats processed to date exhibit some unexpected behavior: i) Iceland Scotland Overflow Water floats that entered the western basin through the Charlie Gibbs Fracture Zone did not follow the Reykjanes Ridge bathymetry into the Irminger Basin as depicted in most schematic diagrams, but instead drifted mostly west-northwestward toward the Labrador Sea or southwestward/southward along the western flank of the Mid-Atlantic Ridge; ii) the only floats that reached the Irminger basin from the Iceland Basin in two years went through deep gaps in the Reykjanes Ridge north of the Charlie Gibbs Fracture Zone; iii) a number of floats deployed in the deep boundary current east of Greenland exhibit behavior consistent with small, energetic DSOW cyclonic eddies that follow the boundary into the Labrador Sea, where they may result in eddy-driven boundary-interior exchange.

Using the Cape Farewell moorings east of Greenland at 60°N, we find that the coastal and slope current velocity cores of the East Greenland Current system are distinguishable, persistent, year-round features. Freshwater transport in the Coastal Current and East Greenland Current on the slope vary seasonally, with staggered maxima in November and February respectively. This may reflect local input of freshwater from Greenlandic glaciers in the coastal current, while freshwater of Arctic origin is advected along the slope.

A key result emerging from the first two years of the Iceland Basin Array is that the transport of the Iceland Scotland Overflow Water plume at the OSNAP line is $5.8 \pm 0.9$ Sv for waters denser than $\sigma_\theta = 27.8$. This transport is larger by almost 2 Sv than previous values obtained farther north in the Iceland Basin, suggesting that additional entrainment into the Iceland Scotland Overflow Water plume occurs as it approaches the southern tip of the Reykjanes Ridge.

A myriad of other OSNAP research projects are underway, many the focus of student and post-doc projects that involve the use of data from the 53°N mooring array, the Angmagssalik mooring array just south of the Denmark Strait, the Extended Ellett Line, satellite, gliders, Argo floats, and RAFOS floats. See here for a full description of these projects.

The OSNAP steering committee meets quarterly via teleconference for the overall supervision of this international project. Additionally, a Data Working Group is focused on the timely delivery of OSNAP data products that will be of interest to the oceanographic community. The OSNAP website continues to publicize OSNAP to the oceanographic community and the public in general and has also served as a venue for information for all OSNAP PIs.

Bibliography


**Figure:** MOC, MHT, and MFT across the full OSNAP section. Shading for each time series indicates uncertainty in the monthly mean estimate, not the intra-monthly variability.
Southwest Atlantic MOC project (SAM)

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Variations in the MOC are thought to have significant impacts on socially important environmental conditions such as precipitation patterns, sea level changes, hurricane intensification, and other extreme weather events. The Southwest Atlantic MOC (SAM) project is designed to measure both the warm-upper and cold-deeper MOC flows near the South Atlantic western boundary at 34.5°S. The SAM array includes four pressure-equipped inverted echo sounder (PIES) moorings deployed by researchers at the NOAA Atlantic Oceanographic and Meteorological Laboratory in collaboration with scientists at the Cooperative Institute for Marine and Atmospheric Studies at the University of Miami. The SAM program began in March 2009, and it also involves partners in Argentina and Brazil, who provide the ship time for deployments, recoveries, and data downloads as well as critical hydrographic observations. The Brazilian partners also augmented the array in December 2012 by adding two current-and-pressure-equipped inverted echo sounder (CPIES) moorings between some of the NOAA instruments (improving the array’s horizontal resolution), and in December 2013 they added a bottom-moored acoustic Doppler current profiler and a bottom pressure recorder up on the continental shelf. In addition to capturing the western boundary MOC flows, the SAM array is also the cornerstone for an international trans-basin MOC array, called the SAMBA. SAMBA is one of the main components of the international SAMOC initiative, including researchers from Argentina, Brazil, France, South Africa, and the United States. The SAM PIES array also complements an existing long-term NOAA program that estimates meridional volume and temperature transports using quarterly trans-basin high-density XBT sections along 34.5°S. Furthermore, SAM data are also useful to the researchers involved in the international Shelf-Deep Ocean interaction program (funded by the Inter-American Institute For Global Change Research), wherein scientists periodically conduct CTD/O₂/LADCP sections from the coast to the location of the furthest inshore SAM mooring, as well as CTD/O₂/LADCP sections along the PIES array during joint cruises.

Recent results
- The NOAA SAM array has now collected just over eight years of continuous daily data.
- The NOAA PIES moorings were successfully recovered and redeployed for the second time in October 2016. Another SAM array data download cruise is underway right now while this report is being written.
- An analysis of the first five years of SAM data has provided insights into the sources of the strongest velocity and transport variability in the DWBC at 34.5°S (Meinen et al. 2017).
- A study of the hydrographic properties in the region has yielded an improved picture of the water mass pathways in the region, identifying previously undetected recirculation cells and strong meandering in the intermediate and deep levels (Valla et al. 2018).
- The parallel French CPIES array on the eastern boundary was recently turned-around, and those records are now four years in length ¾ meaning that it will soon be possible to produce a four-year MOC record from the joint datasets. This will be in addition to the ~200
months already published based on the early NOAA SAM data and an earlier French pilot array on the eastern boundary in 2009–2010.

More information and the data available online: [www.aoml.noaa.gov/phod/research/moc/samoc/sam/](http://www.aoml.noaa.gov/phod/research/moc/samoc/sam/)

**Bibliography**


**Figure:** Time series of DWBC volume transport determined across the full horizontal span of the SAM array and integrated vertically from 800 to 4800 dbar (or the bottom for areas where it is shallower). The total absolute transport is shown (black solid), as are the components relative to an assumed level of no motion at 800 dbar (Relative; blue dashed) and associated with the actual reference layer flow (Reference Layer; red dash-dot). The gray horizontal solid and dashed lines respectively indicate the time mean and the time mean ± two standard errors of the mean (i.e., the 95% confidence limit for the mean value). Figure reproduced from Meinen et al. (2017).
South Atlantic-North Atlantic MOC Linkages: Analysis of the Upper and Lower Limbs With In Situ Instruments

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The MOC plays a crucial role in redistributing water, heat, and salt throughout the global ocean system. MOC slowdowns, shutdowns, and/or changes in the amount of heat and salt carried by the MOC in both the South and North Atlantic are thought to have a pronounced impact on a variety of socially important climate and weather phenomena (e.g., coastal inundation, hurricane intensification, droughts, heat waves). Quantifying and understanding how the Atlantic component of the MOC (hereafter AMOC) changes over time in both hemispheres is therefore crucial for improving our knowledge of how the climate system functions. The overall goal of this project is to advance our understanding of the temporal variability and meridional coherence of the upper and lower AMOC limb pathways in the South and North Atlantic, and to thereby achieve a more holistic view of AMOC. To address this goal we are analyzing \textit{in situ} observations from moored arrays along 34.5°S in the South Atlantic (including NOAA's SAM project) and along 26.5°N in the North Atlantic (including NOAA's Western Boundary Time Series project). We are also working with data from the national and international partners at both latitudes (Argentina, Brazil, France, Germany, and South Africa at 34.5°S, and the University of Miami and the United Kingdom at 26.5°N). This proposed research effort is being led by the project PIs, who will work together with a postdoctoral researcher supported by this proposal.

Recent results:

- A postdoctoral researcher was hired, Dr. Marion Kersalé, via the University of Miami, Cooperative Institute for Marine and Atmospheric Studies, to collaborate with the project PIs on this research project. Dr. Kersalé began working in June 2017.
- In a recently published paper (Meinen et al. 2017), researcher involved in this project worked with colleagues to extend the DWBC time series at 34.5°S to almost six years and evaluated the dynamical sources behind the largest volume transport variations that were observed in that record.
- The project PIs have extended time series of SAM daily bottom pressure and travel time moored records up through October 2016 along 34.5°S. These extended records are being quality controlled and analyzed, and will be used to estimate Brazil Current and DWBC volume transports along 34.5°S over the next 12-18 months in collaboration with both the new postdoctoral researcher (Kersalé) and international partners. Moreover, they will be used in the computation of the daily AMOC variability in collaboration with international researchers.
- The project PIs have extended time series of WBTS daily bottom pressure and travel time moored records up through February 2016 along 26.5°N. Time gaps in these ~12 year records due to instrument failures have been filled where possible using data from nearby RAPID/MOCHA tall moorings. These extended records are being quality controlled and
analyzed, and will be used to update Antilles Current and DWBC volume transports along 26.5°N over the next 12-18 months, and will be compared with observed AMOC signals from the international trans-basin array.

- More than two years of data from the French and South African component of the SAMBA on the eastern boundary (SAMBA-east) at 34.5°S are being used to assess the temporal variability of eastern boundary currents in the South Atlantic Ocean, as well as changes in the volume transport and water mass properties carried by these currents, and how the eastern boundary currents contribute to the strength and variability of the MOC. Kersalé presented a subset of these results during the 2018 Ocean Sciences meeting.
- The aforementioned ongoing SAMBA-east analysis builds upon results from a previous study (Kersalé et al. 2017), which uses overlapping-in-time tall mooring, CPIES, and satellite data to study nonlinear, mesoscale dynamics in the Cape Basin region. That study demonstrates that the upper slope moorings are affected by cyclonic eddies generated at the South Benguela upwelling front, while the deeper slope moorings are affected by the more complex dynamics of the Cape Basin involving Agulhas rings and cyclonic eddies. These complex dynamics induce strong intraseasonal upper-ocean velocity variations and water masses exchanges across the shelf and the open ocean, but also across the subantarctic and subtropical waters. The analysis of four case studies show that exchange of water masses happens through the advection of water by mesoscale eddies, as well as via wide water mass intrusions engendered by the existence of intense dipoles.

**Bibliography**


Figure: Illustration of strong westward propagating features that impact the observed DWBC transport. Velocities from the OGCM for the Earth Simulator (OFES) model at the core of the NADW near 2600 m depth: (a) average over the full 27-year run from 1980–2006; (b) average over August 1987; (c) average over September 1987; (d) average over October 1987; (e) average over November 1987; and (f) average over December 1987. Land is denoted by green; bottom topography (gray shading) is from the Smith and Sandwell (1997) dataset. Yellow line denotes nominal location of the PIES/CPIES array in the real ocean. Magenta disc highlights a propagating eddy and/or wave feature, which ultimately impacts the observed DWBC transport in the model. Modified from Meinen et al. (2017).

Variability, stochastic dynamics and compensating model errors of the AMOC in coupled IPCC models

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During this collaborative project, we explored the interplay of deterministic and stochastic dynamics, and their role in the predictability of AMOC. AMOC simulations in two coupled IPCC GCMs, the GFDL ESM2M and NCAR's CCSM4, were considered.

First, we studied the differences in AMOC variability between preindustrial and 4xCO\(_2\) climates in the GFDL ESM2M GCM (MacMartin et al. 2016). In preindustrial simulations, this model has a peak in the power spectrum of both AMOC and northwards heat transport at latitudes between 26\(^\circ\)N
and 50°N. In the 4xCO$_2$ simulation, the only significant peak is near 60°N (See Figure). Transfer function analysis demonstrates that the shift is primarily due to a shift in internal ocean dynamics rather than a shift in the stochastic forcing. Specifically, the reduction in variance from 25°N-45°N is due to increased stratification east of Newfoundland resulting from shallower and weaker mean overturning. High-latitude variability in the 4xCO$_2$ simulation is related to the advection of anomalies by the subpolar gyre, distinct from the variability mechanism in the control simulation at lower latitudes. The 4xCO$_2$ variability has only a small effect on mid-latitude meridional heat transport, but does significantly affect sea ice in the North Atlantic.

A promising approach to estimate climate dynamics using carefully constructed dynamic forcing experiments has been developed (Kravitz et al. 2017). The application to AMOC is in progress.

Our second focus was a comparison between the preindustrial simulations of AMOC in the GFDL ESM2M and NCAR’s CCSM4 models using LIM. We found in both models that the temperature and salinity at lower levels (1500-2000 m) was more indicative of future AMOC evolution than were these variables at upper levels (0-700 m). Further, neither heat flux nor freshwater flux could be considered part of the deterministic dynamics on annual timescales. However, both heat flux and freshwater flux did play a role in stochastically forcing AMOC in CCSM4, together accounting for about 20% of that stochastic forcing. Stochastic forcing was found to play a minimal role in ESM2M. Behavior of temperature and salinity also differed in these two models. In ESM2M, salinity and temperature appear to vary more or less contemporaneously, while these CCSM4 fields, especially in the lower level, show a markedly different behavior. This difference may underline a difference in the equation of state in these two models, where single variable buoyancy dominates the dynamical behavior of ESM2M, in contrast to CCSM4. In CCSM4, salinity is about three times as important as temperature in its sensitivity to stochastic forcing, whereas salinity and temperature are about equally important in ESM2M.

LIM fits the best first-order linear model with additive stochastic forcing to a multivariate time series. In a related project headed by Bowen Zhao, the LIM formalism was extended to handle second-order linear models. This technique is explained in Zhao et al. (2017), where it is used to show that the NAO may act as white noise forcing of AMOC.

**Bibliography**


SAMOC: Pathways and Modes of Variability

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Previous observational and modeling efforts on the MOC have been focused on the North Atlantic and the Southern oceans, which are the main sites for deep-water formation. To understand the feedbacks between the North Atlantic and the Southern oceans, we need to improve our understanding of the pathways of the upper and lower limbs of the AMOC in the South Atlantic and which are the most important links between them. The South Atlantic is not just a passive conduit for the transit of remotely formed water masses but actively influences them through air-sea interactions, mixing, subduction, and advection. Our research is focused on analysis of the mechanisms controlling the pathways of the upper and lower limbs of the SAMOC and identifying the natural modes of variability in the South Atlantic and their impact on the SAMOC. To address this challenge, we use state-of-the-art eddy-permitting and eddy-resolving NOAA/GFDL climate and ocean-only model simulations, data assimilating models (e.g., SODA and NOAA/GFDL ECDA analysis), process-oriented numerical experiments using ROMs, and global in situ and satellite observations.

Recent results
Multi-decadal satellite and in situ observations were used to examine low-frequency (interannual to decadal) variations of SSH anomalies, upper OHC, water mass properties, ocean circulation, and wind stress curl in the South Atlantic subtropical gyre (between 35°S to 15°S) and the sector just south of the gyre (between 55°S and 35°S). The dominant mode of SSH variability shows interannual to decadal gyre spin-up (positive SSH anomalies in the gyre) and spin-down (negative SSH anomalies in the gyre). Correlations between the box-averaged detrended SSHA within the gyre and the EOFs show that this mode captures more of the gyre variability than the other two modes (r = 0.65). Similar EOF modal structures are reproduced from total steric SSH observations in the upper 700m and 2000m of the water column, as well as from multidecadal numerical simulations from ocean-only, coupled climate simulations, and global ocean reanalyses. Connections between these SSH modes of variability and SAMOC changes (and remote changes in the other basins) are being examined using observations and numerical models by the PIs.

Analysis of two different versions of the SODA model simulations (2.4 and Si3) shows significant correlations between the dominant modes and SAMOC volume transports and SSTs in both the South and North Atlantic. Our analysis also shows a strong correlation between the SAMOC volume transport and MHT.

The volume transport anomalies and the meridional gradient of the SAMOC (and MHT) appear stronger during El Niño years and weaker during La Niña ones (Figure). Interannual variations of SAMOC appear to be strongly influenced by ENSO with warm events producing a strengthening of the SAMOC and cold events producing a weakening (Figure b). The impact of ENSO on the AMOC is restricted to the tropical portions of both basins.
During this period, Perez and Garzoli contributed to a publication (Meinen et al. 2017), which extended the observational record of the lower limb of the AMOC, the DWBC, along 34.5°S to almost six years, and Matano contributed to a study of deglacial changes to the flow through Drake Passage (Roberts et al. 2017).

Bibliography

Figure: (a) Hovmoller diagram of interannual MOC volume transport anomalies in the South and North Atlantic from the SODASi3 simulation. (b) Mean MOC volume transport as a function of latitude. Black lines indicate 1958–2008 mean, red lines indicate El Niño years, and blue lines indicate La Niña years.
Variability of the South Atlantic Subtropical Gyre

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The subtropical gyres are prominent features of the global oceans, forced by the large-scale mid-latitude wind stress curl patterns that form between the easterly trade winds and the subtropical westerlies. The South Atlantic subtropical gyre is bounded on the western side by the southward flowing Brazil Current, on the southern side by the confluence between the Brazil Current and northward flowing Malvinas Current (hereafter Brazil-Malvinas Confluence) and the eastward flowing South Atlantic Current, and on the eastern side by the northwestward flowing Benguela Current and Agulhas leakage, which feed into the westward flowing South Equatorial Current. As part of this study, the time variability of the South Atlantic subtropical gyre is under investigation through analysis and interpretation of satellite and in situ data, synthesis products, and ocean-only and coupled climate data assimilation models.

The overall goals of this project are two-fold: i) to describe the evolution of the South Atlantic subtropical gyre over the past two decades in surface and intermediate waters; and ii) to improve our understanding of the mechanisms that control the variability of the South Atlantic subtropical gyre, and the currents that delineate the boundaries of the gyre, on interannual to decadal timescales. We also want to explore the link between changes in the strength of western and eastern boundary currents in the subtropical gyre and MOC variations in the South Atlantic.

Recent results

- Multidecadal satellite and in situ observations were used to examine low-frequency (interannual to decadal) variations of SSHA of upper OHC, water mass properties, ocean circulation, and wind stress curl in the South Atlantic subtropical gyre (between 35°S to 15°S) and the sector just south of the gyre (between 55°S and 35°S).
- SSHA and heat content in the South Atlantic have been increasing over the past decades but at disparate rates within the gyre (larger heat content trends) and south of the gyre (larger SSHA trends).
- Salinity driven (halosteric) SSHA changes compensate for temperature driven (thermosteric) SSHA changes in the gyre in the upper 700 m of the water column ¾ over the past decade the surface waters in the gyre have become warmer and saltier on average. This halosteric/thermosteric compensation is less prevalent south of the gyre because upper ocean warming is paired with freshening. Water mass changes between 700 and 2000 m also influence SSHA variations, where weak warming is combined with weak freshening in intermediate water layers.
- Once the trend is removed, the dominant mode of SSHA variability shows interannual to decadal gyre spin-up and spin-down with pattern shown in the Figure a. Although this mode captures a small amount of the total variance, it is strongly correlated with SSHA variability within the gyre. Similar EOF modal structures are reproduced from total steric SSHA observations in the upper 700 m and 2000 m of the water column (Figure d,f), pointing to the importance of salinity driven SSHA changes and intermediate water mass changes in the South Atlantic.
During this period, Perez also contributed to a publication (Meinen et al. 2017), which extended the observational record of the lower limb of the AMOC, the DWBC, along 34.5°S to almost six years, as well as studies using moored and satellite data to study interannual variations in the Brazil Current along 34.5°S (led by M.P. Chidichimo), and EBC variability in the Cape Basin region along 34.5°S (led by M. Kersalé).

Bibliography

**Figure:** Spatial patterns of the first EOF mode computed from annual mean detrended SSHA from AVISO from 65°W to 25°E and from 55°S to 10°S from 1993 to 2015. EOF 1 computed from World Ocean Database (WOD) thermosteric SSHA computed in upper 700m for different b) 2005-2015, c) 1993-2015, and e) 1955-2015. The remaining show EOF 1 computed from WOD total steric SSHA computed in the upper d) 700m and f) 2000m.
The overall goal of this study is to obtain a quantitative description of the water mass composition, kinematics, and dynamics of the Atlantic water boundary current in the eastern Arctic Ocean over an annual cycle in order to elucidate the role of the current in regulating the Arctic system.

This is part of a larger cooperative project entitled the Atlantic Water Inflow Experiment (ATWAIN), which is an international collaboration between six institutions: The Woods Hole Oceanographic Institution (WHOI); the Institute for Marine Research in Bergen, Norway (IMR); the Norwegian Polar Institute (NPI); the University of Svalbard (UNIS); the University of Tromsø (UT); and the Institute of Oceanology Polish Academy of Sciences (IOPAS). Together we deployed six moorings across the Atlantic water boundary current near 30°E for a one-year period, from September 2012 to September 2013 (Figure 1). WHOI provided four of the offshore moorings in the array. In addition to the mooring work, we carried out two shipboard hydrographic/velocity surveys in the region surrounding the array, one during the deployment cruise and the other during the recovery cruise. At this point the WHOI mooring data have been uploaded to the NCEAS Arctic Data Center, and the scientific analyses are continuing.

**Recent results**

- The year-long average transport of the Atlantic water boundary current north of Svalbard is 2.08 ± 0.24 Sv to the east. The vertical section of mean absolute geostrophic velocity (Figure 2) shows that the current is mid-depth intensified and banked against the upper continental slope. Its core velocity is O(15 cm s⁻¹). This is the first robust transport estimate of the current.
- The hydrographic properties of the current vary seasonally: the Atlantic water is warmest and saltiest in late fall/early winter. The transport is maximum from September to mid-December and minimum between April and August: 2.44 ± 0.12 Sv and 1.10 ± 0.06 Sv, respectively.
- The annual cycle in Atlantic water temperature and salinity at the array site is significantly different than the inflowing Atlantic water at Fram Strait. We attribute this to local air-sea interaction. In late fall, mixed layers deepen to greater than 300 m and the Atlantic layer is directly ventilated in the presence of a partial ice cover.
- During the year the mooring array detected the presence of eddies whose diameters ranged from 30-100 km, extending as deep as 600 m. Both anti-cyclones and cyclones were observed. The former had warm, salty cores and are believed to have spawned from the boundary current.
Bibliography

**Figure 1:** Location of the mooring array and instrument configuration in the eastern Arctic Ocean.

**Figure 2:** Year-long averaged absolute geostrophic velocity. Positive values are eastward. The dashed white lines denote the Atlantic water layer.
Ventilation of Denmark Strait Overflow Water in the Iceland and Greenland Seas

PIs: M. Spall and R. Pickart
Woods Hole Oceanographic Institution

The focus of this work is to better understand where and how the densest waters that form the Denmark Strait Overflow are formed and transported to the sill. Recent observations indicate that half of the densest overflow water emanates from the North Icelandic Jet, which is found along the north slope of Iceland. This grant will carry out a wintertime field program in the Iceland and Greenland Sea and regional, high-resolution modeling study, coordinated with international field programs, to advance our knowledge of this newly identified source and its link to the AMOC.

Due to unavailability of a research vessel, the field phase of the project was delayed by one year to winter 2017/18. At this point a vessel has been identified (the NRV Alliance), and the dates of the cruise are set. A planning meeting was held at Alliance’s home port that addressed some of the logistics of the cruise. A science meeting also took place where the aircraft operations were discussed along with issues concerning coordination of the ship and plane. A final logistics meeting will occur in late fall. On the science front, recently collected data (shipboard measurements and mooring time series) were analyzed to address various aspects of the dense water feeding Denmark Strait and the relationship of this overflow water to the incoming subtropical water to the Iceland Sea Although properties of the inflow and outflow co-vary, suggesting cause and effect, it was argued that the year-to-year variability of E-P over the Iceland Sea strongly influences the salinity of the outflow. A numerical model was used to shed light on the higher frequency variability of the Denmark Strait Overflow.

This grant also helped support several other studies more broadly related to the project goals. An idealized theoretical model of the water mass transformation within the Nordic Seas, represented as a “double estuary,” was developed that focused on the influence of freshwater runoff within the Nordic Seas on the water mass transformation and transports between the subpolar North Atlantic and the Nordic Seas (Lambert et al. 2017). Another study looked at the exchange across the sill driven by wind.

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**The Norröna Project: An International Collaboration for Sustained Studies of the Meridional Overturning Circulation between Denmark, the Faroes and Iceland**

PIs: T. Rossby¹, C. Flagg²

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The long-range objective of this project is to measure directly the exchange of water, heat and salt between the northeast Atlantic and the Nordic Seas between Scotland, the Faroes, and Iceland. The approach is straightforward, to operate an ADCP in the hull of the high-seas ferry Norröna that operates between Denmark, Torshavn in the Faroes, and Seyðisfjörður, Iceland, to scan the currents repeatedly along the vessel’s route. The 75 kHz ADCP, which reaches to greater than 500 m in the Faroe-Shetland Channel (FSC) and to the bottom over the Iceland-Faroe Ridge (IFR), has been collecting data since March 2008. Collection in the FSC is year-round but limited to the summer months for the IFR due to high swell conditions in winter that lead to the drawdown of bubbles under the vessel. Three papers have been published and another is nearing completion.

This new study combines eight years of repeat ADCP measurements between Shetland (Scotland), the Faroes, and Iceland with more than three years of monthly XBT temperature sections to estimate volume and heat transport between the northeast Atlantic and the southern Nordic Seas. By using archived hydrographic data along the vessel tracks we can also estimate salt mean salt fluxes. This study is further strengthened thanks to a recent 10-month long study of top-to-bottom measurements of currents, temperature and salinity from 12 moorings deployed across the Blosseville Basin between Iceland and Greenland. Thus, when the study soon is ready, we will hopefully have the most accurate estimates obtained so far of volume, heat, and fresh water fluxes between Greenland and Europe.

**Bibliography**

The Oleander Project: High-resolution observations of the dynamic ocean between New Jersey and Bermuda

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\textsuperscript{4}Bermuda Institute of Ocean Sciences

Since late 1992, high-horizontal resolution upper-ocean velocity has been sampled by an ADCP mounted in the hull of the container vessel \textit{CMV Oleander}, which operates on a weekly schedule between New Jersey and Bermuda. In addition to velocity, the Oleander Project includes thermosalinograph (TSG) and monthly XBT — using the Autonomous eXpendable Instrument System, AXIS — sections that span the route. The Oleander Project is funded by NSF with contributions from NOAA. The ADCP data acquisition system has been upgraded to a modified version of UHDAS — the software system used on most UNOLS vessels. This modification enables real-time processing, immediate transmission of data, and two operating ADCPs. We continue to deliver data via the Oleander website and have included several downloadable files of Gulf Stream North Wall position and upper ocean fluxes along the Oleander line through the project website: oleander.bios.edu.

Our goal is to provide sustained measurements of ocean currents and temperature across four distinct regions: the continental shelf, slope sea, Gulf Stream, and northwestern Sargasso Sea. Specifically, our objectives are to continue the Oleander velocity program to elucidate long-term climatological variability and to provide near-real-time processed data distribution to enable broad community participation in scientific analysis.

The Oleander dataset shows no evidence of a decrease in Gulf Stream transport. Here we update the Rossby et al. 2014 estimate and extend our Gulf Stream transport time series to mid 2016 (Figure). Again, there is no clear evidence of a decrease. The small trend (blue line) is a factor of two to four times less than accelerated US sea level rise north of Hatteras, and, moreover, the trend is not statistically significant (95% confidence levels).

A new vessel will replace the CMV Oleander in late 2018 or early 2019. This will provide an opportunity for ADCP enhancements. A 150 kHz ADCP will provide observation of near-surface and shelf waters, and a 38 kHz ADCP will measure currents through the base of the thermocline.

\textbf{Bibliography}
**Figure**: Updated from Rossby et al. (2014) Figure 2. Annually averaged Gulf Stream surface layer flux (termed layer transport) stepped every half-year (black line). The red lines indicate the 95% confidence limits of the linear fit (blue line). Note the large ~8% extrema around 1994, 2003, 2007, and 2012. The right axis shows 0-2000 m transport assuming a scale factor of 700. The Gulf Stream is the region of flow parallel to the maximum velocity vector between the zero crossings on either side of the maximum.

**Observed transports of the MOC at several latitudes in the Atlantic**

**PIs**: C. Schmid\(^1\) and G. Halliwell\(^1\)

**Postdoc**: Sudip Majumder\(^2\)

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Our project focuses on computing transport indexes for monitoring the MOC in the South Atlantic Ocean at selected latitudes. To accomplish this, a method for deriving monthly three-dimensional fields of absolute velocity in the upper 2000 m of the ocean developed by the PI is used to calculate to study the circulation during the Argo period. The method is based on *in situ* observations from Argo (profiles and subsurface drift) that are complemented with daily fields of SSH from satellite altimetry (AVISO). The derived velocity fields and hydrographic fields from Argo are used in conjunction with the monthly World Ocean Atlas and Ekman transports to derive time series of the monthly means of the MOC strength and meridional heat transport across selected latitudes. The time series was expanded to cover the years 1993 to 2015. The methodology has been evaluated by comparing the derived transports with estimates from independent
observations derived from XBT transects between 24°S and 35°S, as well as other published results. An expansion into the North Atlantic was completed recently. In addition, daily time series are produced at selected latitudes. At 26.5°N the derived transport time series compares well with the estimates from the RAPID/MOCHA Array.

**Recent results**

- South Atlantic: MHT from Argo and altimetry increases from 0.64 ± 0.39 PW at 35°S to 0.89 ± 0.25 PW at 30°S, 0.81 ± 0.15 PW at 25°S, and decreases to 0.71 ± 0.18 PW at 20°S. The corresponding strengths of the MOC are: 19 ± 4 Sv, 26 ± 5 Sv, 23 ± 2 Sv, and 20 ± 2 Sv, respectively.
- North Atlantic, 26.5°N: 15 ± 4 Sv and 1.09 ± 0.37 PW agrees well with 17 ± 5 Sv and 1.11 ± 0.35 PW from MOCHA/RAPID
- North Atlantic, 37°N: 18 ± 3 Sv, 0.63 ± 0.47 PW
- The seasonal variability is dominated by annual cycle at 37°N, 35°S, 30°S, and 25°S. In the South Atlantic, the maximum occurs in May to June, and the minimum in September to November. A semi-annual cycle is also detected at 20°S, with the maxima in May and December and the minima in January and September. At 26.5°N, the annual cycle is also dominant, but the mean spectral peak is wider than at other latitudes. And there is a small peak at the semiannual period. The maxima are in January and July, and the minima in May and September.

**Bibliography**


**Figure:** (Left) Time series of MOC strength and MHT at 26.5°N (black: from Argo and altimetry; red: MOCHA/RAPID). (Right) Wavelet analysis of the time series from Argo and altimetry.
Modeling Effects of Ice Sheet Changes on AMOC Variability

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We have investigated impacts of ice sheet variations on the AMOC. Projections of the future AMOC evolution, such as performed for the IPCC Assessment Reports, do not typically include ice sheet melting even though we know that the AMOC is sensitive to freshwater input into the North Atlantic and that the Greenland ice sheet is projected to accelerate melting in the future. Here we have organized an international model intercomparison project (AMOCMIP) that focused on including Greenland ice sheet melting in future projections. We have developed a protocol that includes realistic amounts and distributions of Greenland ice sheet meltwater for two emission scenarios (RCP4.5 and RCP8.5). We have conducted simulations with and without Greenland ice sheet melt by seven state-of-the-science GCMs. We have also developed an AMOC emulator in order to perform probabilistic AMOC projections including Greenland ice sheet melting until the year 2300. We have also investigated the effects of Antarctic ice sheet variations during the Holocene on global and regional climate variability and the AMOC.

Recent results
AMOCMIP results show that Greenland ice sheet melting leads to a significant additional AMOC reduction in some models but not in others. Overall the GCMs project a consistent reduction of the AMOC for RCP4.5 until about year 2100 after which it recovers or stabilizes. In contrast, for RCP8.5 the AMOC continues to weaken until year 2300. Probabilistic simulations using an emulator (Bakker and Schmittner 2016) fitted to the AMOCMIP results support the finding that GIS melting can decrease the AMOC further, although its effect is smaller than that of warming and changes in the hydrological cycle (Figure). By years 2090-2100, the AMOC weakens by 18% [-3%, -34%; 90% probability] in an intermediate greenhouse-gas emission scenario and by 37% [-15%, -65%] under continued high emissions. Afterward, it stabilizes in the former but continues to decline in the later to -74% [+4%, -100%] by 2290-2300, with a 44% likelihood of an AMOC collapse. The emulator results indicate that including Greenland ice sheet melting increases AMOC collapse probabilities. These results suggest that an AMOC collapse can be avoided by CO₂ mitigation (Bakker et al. 2016a).

We used freshwater fluxes simulated by a high-resolution model of the Antarctic ice sheet over the Holocene to force the University of Victoria climate model. The Antarctic ice sheet model, which was forced by variable surface and subsurface ocean boundary conditions, simulates significant multi-centennial variability in freshwater fluxes. These fluxes result in significant variability of surface and subsurface temperatures, mainly in the Southern Ocean but also elsewhere, and AMOC variability. We propose a positive feedback, whereby Antarctic ice sheet melting from subsurface ocean warming results in meltwater fluxes, which stabilizes the water column in the Southern Ocean, thereby amplifying the subsurface warming. Both Antarctic ice sheet and
ocean dynamics act as low pass filters such that this positive feedback works on multi-centennial timescales (Bakker et al. 2016b).

**Bibliography**


**Figure:** Probabilistic AMOC projections for RCP4.5 (top) and RCP8.5 (bottom). From Bakker et al. (2016a).
The objective of the MOVE project is to maintain an operational observing system to continuously sample the strength of the lower branch of the AMOC at 16°N. The system extends from the western boundary near Guadeloupe to the Mid-Atlantic Ridge, and delivers moorings and seafloor instrument records that started in 2000. In early 2017, MOVE carried out fieldwork to telemetrically retrieve subsets of the data and service some seafloor instrumentation. The Figure shows a map of the measurement locations and the resulting time series of southward transport across the array. Scientific analyses are ongoing and focusing on comparing the MOVE data with other observational records and results from numerical simulations. Two presentations about these analyses were shown at the 2017 US AMOC Science Team Meeting. Recent publications are those by Elipot et al. (2017) and Baringer et al. (2017). The latter is a continuation of annual contributions to the “State of the Climate” reports, to which MOVE has contributed since 2011.

MOVE website with current information: http://mooring.ucsd.edu/projects/move/move_intro.html

**Bibliography**


**Figure:** Location of the three active MOVE sites (left) and resulting time series (right) of sea water volume transported across the section in the depth layer 1200-5000 m. There was stronger southward transport (denoted by negative sign) in the earlier years, and again in recent years, with weaker southward flow in between, highlighting interannual variability of the flow field. The dashed line at the end of the time series denotes transports computed from recently telemetered subsets of the data. Adapted from Send et al. (2011).
Forced Transients in Water Mass Transformation and the Meridional Overturning

PI: M. Spall
Woods Hole Oceanographic Institution

The objective of this program is to develop a theoretical understanding of how the thermohaline circulation responds to transients in atmospheric forcing. Quantities of interest include the ocean circulation, extent of deep convection, MHT, MOC, and the temperature and salinity of product waters.

Recent results
Mesoscale eddies are known to play an important role in communicating buoyancy anomalies between boundary currents and regions of atmospheric forcing in basin interiors. Building on previous results, supported by this grant, on the maintenance of the Beaufort Gyre through a balance of Ekman pumping and lateral eddy fluxes, a more general theory for the low-frequency response of the ocean to time-dependent forcing was developed. Eddy fluxes generated from a slowly evolving large-scale mean flow retain a memory of previous states of the ocean. For typical parameters, this time scale is $O(5-10)$ years. As a result, eddy fluxes remain out of balance with the forcing if the forcing varies on decadal timescales. This introduces enhanced variance in the large-scale flow state on these timescales. An improved eddy flux parameterization that takes this “eddy memory” into account was developed and tested against eddy resolving models (Manucharyan et al. 2017). The configuration used was representative of the Beaufort Gyre, but similar dynamics are expected to be relevant for any region where eddy fluxes are important for the large-scale mean balances, such as the Southern Ocean and in regions of deep convection.

Bibliography
Dynamics of Cross-Equatorial Flow

PI: M. Spall
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The focus of this work is to better understand how the mid-depth waters of the MOC cross the equator. Basic potential vorticity considerations indicate that the equator poses a unique dynamical transition for flows crossing from one hemisphere to the other. The change in the sign of planetary vorticity implies that some non-conservative process must become active if these waters are to be advected outside the equatorial band. Mechanisms related to lateral and vertical mixing on momentum and buoyancy, and their potential vorticity connections to the large-scale mean and eddy field, are being identified. The approach makes use of idealized, high-resolution numerical models and theory.

The first configuration used two layers with very high resolution (high Reynolds number) to allow for a separation between the width of the inertial boundary layer, which is \(O(10\, \text{km})\), and the viscous sublayer, which is \(O(1\, \text{km})\). This results in very unstable boundary currents and places a significant burden on the exchange between the inviscid interior and the viscous sublayer to dissipate potential vorticity. Analysis of these calculations is underway.

The second configuration considers the role of equatorial and western boundary current dynamics in controlling the equilibrium and low frequency variability of the mid-depth stratification in the Atlantic basin. Theoretical estimates relate the thickness of the NADW layer in the basin interior to the source strength, domain size and latitude, and the dynamics of western boundary currents. The theory also predicts the adjustment timescale for anomalies in the source strength and the response for oscillatory, periodic forcing. An example demonstrating the development of the mid-depth stratification under steady forcing is given below.

**Figure:** (Left) Basin-averaged NADW layer thickness for a case with an 11 Sv source and initially no NADW present in the basin. Solid line is from a numerical model; the dashed line is from the theory. (Right) Inflow (Northern Hemisphere) and outflow (Southern Hemisphere) transports as a function of time. System equilibrates when the outflow balances the inflow. The adjustment, for this basin configuration, is on \(O(20\, \text{years})\) and well predicted by the theory.
Mechanisms of Freshwater Exchange Across the East Greenland Shelf

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The exchange of freshwater between the east Greenland shelf and the interior of the subpolar North Atlantic and Nordic Seas is a key element in the maintenance and variability of the AMOC and its sensitivity to changes in atmospheric forcing and freshwater outflow from the Arctic Ocean.

Two year-long, high-resolution (~ 2 km) numerical simulations covering the east Greenland shelf and the Iceland and Irminger seas have been set up and run. The two simulations are identical, except that one is forced by a global reanalysis atmospheric product and the other is forced by a high-resolution regional reanalysis. These datasets and analysis tools have been made publically available at sciserver.org. The model hydrography and circulation in the vicinity of Denmark Strait have been meticulously compared with available observational datasets. The variability in Denmark Strait has been investigated by detecting and characterizing the dominant mesoscale features. These boluses and pulses have been studied, taking advantage of the high-resolution numerical model. The results indicate that the mesoscale features play a major role in controlling the variability of the Denmark Strait Overflow transport into the Irminger Sea (Almansi et al. 2017). Further analysis and comparisons with observations are underway.

Two additional studies have focused on the transport of low salinity water out of fjords and across the shelfbreak into the basin interior driven by katabatic winds. In the first, idealized model runs, theory, and observations in Sermilik Fjord were used to understand this wind-driven exchange and to estimate that about 10% of the low salinity surface layer gets transported out of the fjord by a typical katabatic wind event. There are four to eight events per year, so this represents an important exchange mechanism (Spall et al. 2017). The second study considered the ability of these narrow, intense wind events to force low salinity water across the shelfbreak topography and into the interior, where it may inhibit deep convection. Idealized nonlinear models and linear quasigeostrophic theory were used to identify key nondimensional numbers that control the exchange across the topography and to estimate the volume flux into the basin interior for conditions typical of southeast Greenland (Spall and Pedlosky 2017).

Another study that was partially supported by this grant used shipboard hydrographic and velocity sections to quantify the North Icelandic Jet and the North Icelandic Irminger Current (Pickart et al. 2017). Analysis included the mean structure and transports and their low-frequency variability. It was argued that the variability is influenced by subpolar winds (for the inflow) and precipitation over the Iceland Sea (for the outflow).

Bibliography


**Figure:** Simulation of a typical katabatic wind event. (a) Pattern of wind stress applied in the model. The fjord is the narrow yellow region centered at x=190 km, y > 50 km. b) Wind stress amplitude as a function of time relative to the peak of the katabatic wind event. Bold solid line is the average wind event based on met station measurements; thin solid line is the wind stress used for the model. Dashed lines are for the along-shelf wind stress (bold reanalysis product, thin used for the model). (c) Along-fjord velocity at 50 m depth, mid-fjord. Bold line is observations; thin lines are model with (solid) and without (dashed) the along-shelf component of the wind. The agreement is reasonable in terms of the amplitude, sign, and phase of the response. From Spall et al. (2017).
Wave processes along 26°N

PIs: Z.B. Szuts¹, K.I. Martini²
¹University of Washington
²Sea-bird Scientific

This project studies oceanic waves over a broad spectrum by analysis of mooring observations collected by the 26°N AMOC array. With high-resolution sampling sustained since 2004, frequencies from internal gravity waves (internal tides and inertial frequencies) to year-long planetary waves are resolved, along with variability from fortnightly to interannual timescales.

For long period planetary waves, it is well known that the dominant open ocean signal is seen in SSH (e.g., Szuts et al. 2012), and coherence between moorings is slight at the western boundary (e.g., Clément et al. 2014) and non-existent across the rest of the basin. Therefore, our approach is to focus on energy and the vertical structure at each mooring sites. For short period waves, internal tides, and inertial oscillations, these measurements span an ocean basin with different topographic regimes (boundary, open ocean, and mid-ocean ridges) across which internal waves can propagate. Vertical structure and energy at and between each site are examined to determine sources, sinks, and long-range internal wave propagation.

Recent results
Semi-diurnal internal tides are the largest signal at 26°N but are only phase-locked with the forcing barotropic tide at the eastern boundary (Martini and Szuts 2016). This motion is episodic at the Mid-Atlantic Ridge and is weak enough at the western boundary to be often obscured by background variability. There is evidence of onshore propagation onto the western boundary but not of cross-basin propagation across the rest of the section. Inertial waves are tied to atmospheric forcing. They are strongest in the fall and winter, corresponding to hurricane and North Atlantic winter storm seasons. Two hurricanes passed near the array and provide a unique picture of the deep ocean's response to strong surface forcing.

For long period motion, the decrease of water-column-integrated kinetic and potential energy decreases strongly close to the western boundary. Though this is consistent with the known decrease of variability at the western boundary, our results present convincing evidence that the nature of this decrease does not support a linear reflection of westward-propagating Rossby waves. To calculate wave energy fluxes, or $F=\rho'v'$, a calculation often done for high-frequency tidal and inertial internal waves but rarely for low-frequency planetary waves, we have implemented a filter bank that band-passes the single-instrument records (of density and velocity) prior to calculating depth-integrated energy. This approach is necessary to obtain directional (signed) values of energy flux (Figure). These results are more varied than expected and do not meet the prior expectations of westward energy flux ($F_x < 0$) carried by long Rossby waves and of southward energy flux ($F_y < 0$) at all frequencies. Our continuing work seeks to interpret these results.
**Bibliography**


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**Figure:** Energy flux from the four western boundary moorings in band-passed frequency bands, for the zonal componen ($F_x$, left) and the meridional component ($F_y$, right).
Sources and Impacts of Variability of the Meridional Property Transports in the Atlantic Ocean

PI: L. Thompson and K. Kelly (retired)
University of Washington

The goal of this study is to explain the causes of interannual to decadal anomalies of meridional heat and freshwater transport in the Atlantic Basin using analysis of observations. We use both in situ and satellite observations to investigate the relationship between OHC anomalies and changes in ocean circulation, and air-sea heat exchange.

Recent results
We analyzed the response of Atlantic heat and freshwater transports to the recent AMOC slowdown. A decline in southward freshwater transport results in freshwater convergence in the North Atlantic, which is largely countered by a decrease in precipitation. The anomalously high salinity during the slowdown supports modeling studies that suggest that heat, not freshwater, drives trends in the AMOC over recent decades (Kelly et al. 2016).

Investigation of the linkages between interannual variability in Florida Current transport from underwater cables, AMOC at 26°N, and changes in the Gulf Stream strength and position from satellite altimetry showed that an increase in upper mid-ocean transport at 26°N leads to a northward shift in the Gulf Stream path, while an increase in the Florida Current leads to an increase in Gulf Stream strength downstream of the New England Seamounts.

We also find that the downward trend in AMOC over the last decade occurs at the same time as a decline in the Gulf Stream strength. The spatial structure of the trend in sea level is very similar to the response of sea level on interannual time scales to AMOC indicating that much of the observed changes in the subtropical Atlantic are likely driven by mid-latitude wind-stress variability.

An analysis of the relationships between satellite altimetry as a proxy for upper OHC and surface turbulent heat exchange show that on interannual timescales, in the northern and southern recirculation gyres of the Gulf Stream and the North Atlantic Current OHC anomalies driven by ocean heat transport convergence control air-sea heat exchange.

Bibliography

**Figure:** Trend in altimetric SSH 2004–2015 (cm yr⁻¹). The blue line indicates the location of the New England Seamounts. Downstream of the New England Seamounts, the sea level increases to the north of the Gulf Stream and decreases to the south indicating a reduction in Gulf Stream strength. Over the same time period, AMOC at 26°N decreased, mostly owing to a decrease (southward increase) in the upper mid-ocean transport (UMO) consistent with a lowering of heat content in the subtropics. This spatial pattern is also found in a regression between interannual sea level and UMO.

**Completing a 10-Year Record of Deep Western Boundary Current Observations at Line W: A Contribution to the AMOC Study**

PIs: J. Toole¹, M. Andres¹, R. Curry¹, T. Joyce¹, M. McCartney¹, W. Smethie², and I. Le Bras³

¹Woods Hole Oceanographic Institution
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³Scripps Institution of Oceanography

The Line W program was designed to observe interannual water property variability and transport changes in the North Atlantic's DWBC and Gulf Stream and to investigate their causes and consequences for the climate system. Data from a sustained moored array and repeated occupation of a hydrographic section provide a 10-year-long time series of boundary current variability that is being used together with observations from companion programs at other
latitudes in the Atlantic to characterize the North Atlantic's MOC and its meridional connectivity. The field program was completed with a final cruise aboard R/V Knorr (May 1–12, 2014) during which the six moorings in the array were recovered and the hydrographic section was again reoccupied. In the time since, the moored and shipboard data have been processed and (ongoing) analysis of the observations conducted. Le Bras, who was supported on this project, completed her dissertation research that investigated the DWBC and its interaction with the Gulf Stream in December 2016. Finalized mooring and cruise datasets have been submitted to the OceanSites data archive; data are also available on our project website: http://www.whoi.edu/science/PO/linew/index.htm.

**Recent results**

Collection of hydrographic observations southeast of Woods Hole spanning 1995–2014 reveal water mass changes consistent with changes in source water properties upstream in the Labrador Sea. This is most evident in the cold, dense, and deep class of Labrador Sea water that was created and progressively replenished and deepened by recurring winter convection during the severe winters of 1987–1994. The arrival of this record cold, fresh, and low potential vorticity anomaly at Line W lags its formation in the Labrador Sea by three to seven years. The consistency of the data with realistic advective and mixing timescales was assessed using the Waugh and Hall (2005) model framework. The data are found to be best represented by a mean transit time of five years from the Labrador Sea to Line W, with a leading order role for both advection by the DWBC and mixing between the boundary flow and interior waters.

Daily profiles of subinertial velocity, temperature, salinity and neutral density were constructed for each Line W mooring site and cross-line DWBC transport time series were derived for specified water mass layers. Time-average transport estimates were made and modes of DWBC transport variability were investigated through compositing. Integrating the daily velocity estimates over the neutral density range of 27.8–28.125 kg m\(^{-3}\) (encompassing Labrador Sea and overflow water layers), a mean equatorward DWBC transport of 22.8 x 10\(^6\) m\(^3\) s\(^{-1}\) ± 1.9 x 10\(^6\) m\(^3\) s\(^{-1}\) was obtained. A statistically-significant trend of decreasing equatorward transport was observed in several of the DWBC components as well as the current as a whole, with the largest linear change (a 4% decrease per year) in the layer of Labrador Sea Water that was renewed by deep convection in the early 1990s, whose transport fell from 9.0 x 10\(^6\) m\(^3\) s\(^{-1}\) at the beginning of the field program to 5.8 x 10\(^6\) m\(^3\) s\(^{-1}\) at its end. In contrast, no long-term trend was observed in upper-ocean slope water transport.

Motivated by the proximity of the northern recirculation gyre and DWBC in the North Atlantic, an idealized model was used to investigate how recirculation gyres and a deep flow along a topographic slope interact. In this two-layer quasi-geostrophic model, an unstable jet imposed in the upper layer generates barotropic recirculation gyres. The northern recirculation gyre's adjustment to the slope leads to increased eddy PV fluxes at the base of the slope that stir the deep current and recirculation gyre waters. The deep current is a primarily passive component of the present model, but in some cases the deep current also acts to damp eddy growth in the unstable jet. These mechanisms may shape the circulation in the western North Atlantic, with potential feedbacks on the climate system.
**Bibliography**


**Figure:** (Left) Map of the Northwest Atlantic Ocean bathymetry (shading with color bar over land) showing the location of the Line W moorings (blue dots) and time-average axis of the Gulf Stream (red line, taken as a specified mean sea surface height contour). The yellow arrows depict the mean surface geostrophic velocity on Line W in the 2004–2014 period, based on altimetric SSH for the subset of times when the Gulf Stream and its north wall were near their mean crossing latitudes at the line and there were no strong surface velocity anomalies in the slope water. (Right) Composite Line W across-line velocity section constructed from observations from the same subset of days. Positive velocities are to the northeast; contour interval is 1 cm s\(^{-1}\) for equatorward flows and 10 cm s\(^{-1}\) for poleward velocities; the thick black lines mark the zero isobach and locations of the moorings.
Influence of the equatorial Atlantic cold tongue and Angola current on Atlantic basin climate variability

PIs: E. K. Vizy and K. H. Cook
The University of Texas at Austin

This NASA funded project seeks to better understand the ocean-atmosphere interactions of southeastern Atlantic Ocean features including the cold tongue, the Angola Current, and the Angola-Benguela frontal zone, and how these interactions are linked to regional and remote Atlantic climate variability. To meet this objective a combined observational analysis/coupled regional climate model approach is utilized. The primary impact of this knowledge is that it can be used to improve current and future numerical weather prediction over the South Atlantic.

**Recent results**

Two, second generation atmospheric reanalyses are analyzed to improve our fundamental understanding of the annual cycle of the South Atlantic subtropical high (SASH) as well as examine how its interannual variability relates to climate variability in Sun et al. (2017). Seasonal composites and EOF analysis indicate that meridional changes in the position of the SASH dominate interannual variations in austral summer. In particular, the anticyclone tends to be displaced poleward in La Niña years when the southern annular mode is in its positive phase and vice versa. In southern winter, multiple processes operate in concert to induce interannual variability and none of them appears to dominate.

A regional climate model coupled to an intermediate-level mixed layer ocean model (CRCM) is used to advance our understanding about how the ocean mixed layer in the Benguela upwelling region is connected to variations of the SASH and land surface processes over southern Africa in Sun et al. (2018). Results indicate that in austral summer, zonal displacements of the SASH can induce variations of mixed-layer currents in the Benguela upwelling region through surface wind stress curl anomalies near the Namibian coast. During austral winter, variations of the mixed layer Ekman transport in the Benguela upwelling region are connected to the strength of the SASH through its impact on both coastal wind stress curl and alongshore-surface wind stress.

We used the CRCM to advance our understanding of how and why the Angola-Benguela frontal zone (ABFZ) in the southeastern Atlantic has changed over the 1980–2014 period in Vizy et al. (2018). Results indicate a consensus that there has been a poleward shift since 1980 in the annual mean ABFZ position, ranging from 0.05° to 0.55° latitude per decade. There is also agreement that the annual mean ABFZ intensity is strengthening, ranging from 0.05 to 0.13 K 100 km\(^{-1}\) per decade. This intensification is associated with ocean mixed-layer warming (cooling) equatorward (poleward) of the ABFZ. CRCM results are analyzed to better understand these changes.

**Bibliography**


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**Subpolar-Subtropical Connectivity of the North Atlantic Circulation**

**PIs:** X. Xu and E. P. Chassignet  
Florida State University

The objectives of this program are i) to explore the dynamics that are responsible for the three-dimensional circulation in the transition region in the western Newfoundland Basin, and ii) to document the role of this relatively small region play in the large-scale North Atlantic Circulation.

**Recent results**

It is generally recognized that a minimum resolution of 1/10° is required for a proper representation of mid-latitudes’ western boundary currents and associated eddies. A 1/10° grid spacing, however, is not sufficient to resolve the Rossby radius of deformation with two grid points at all latitudes and, therefore, does not allow for a proper representation of baroclinic instability and associated eddies throughout the domain. Despite the major improvements observed with 1/10° grid spacing, the solutions remain extremely sensitive to choices in boundary conditions and subgrid-scale parameterizations, and there is a continuous need to quantify the value added of increased resolution. In a recent work (Chassignet and Xu 2017), we investigated the impact of horizontal resolution in eddying regime (1/12° to 1/50° or 6 to 1.5 km at mid-latitudes) on Gulf Stream separation, penetration, and variability is quantified in three identical North Atlantic experiments. This study shows that:

- The representation of Gulf Stream penetration and associated recirculating gyres shifts from unrealistic to realistic (see Figure) when the resolution is increased to 1/50°. This is consistent with Hurlburt and Hogan using the six-layer hydrodynamic NLOM model and by Lévy et al. (2010) using the NEMO model in an idealized domain. In all cases, the nonlinear effects of the submesoscale eddies intensifies the mid-latitude jet and increases its penetration eastward.
- The penetration into the deep ocean drastically increases with resolution and closely resembles the observations.
- Surface power spectra in the 70–250 km mesoscale range are independent of the horizontal resolution and the latitude and are representative of 2D quasigeostrophic and surface quasigeostrophic turbulence.
Bibliography

Figure: Eddy kinetic energy (EKE, in cm² s⁻²) in the Gulf Stream region computed from SSH derived geostrophic velocities, based on a) AVISO 1993–2012, and b-d) 1/50°, 1/25°, and 1/12° HYCOM simulations.

Evaluation and Diagnosis of the AMOC 3D Structure in Climate Models

PIs: X. Xu¹, E. P. Chassignet¹, M. O. Baringer², S. Dong²
Collaborators: P. Rhines³
¹Florida State University
²NOAA Atlantic Oceanographic and Meteorological Laboratory
³University of Washington

The overall goals are i) to derive a better and more comprehensive diagnosis for evaluating the AMOC representation, including time mean structure and temporal variability, in current climate models, and ii) to identify and understanding the key physical processes or mechanisms that lead to the wide spread of the mean AMOC state as well as the AMOC variability among the CMIP5 models.
**Recent results**

Diapycnal water mass transformation is the essence behind the AMOC and the associated heat and freshwater transports. Existing studies have mostly focused on the transformation that is forced by surface buoyancy fluxes, and the role of interior mixing is much less known. Xu et al., (2017) maps the three-dimensional structure of the diapycnal transformation, both surface-forced and mixing-induced, using results of a high-resolution numerical model that have been shown to well represent the large-scale structure of the AMOC and the North Atlantic subpolar subtropical and gyres. The analyses show that:

- Annual-mean downward transformation takes place seamlessly from the subtropical to the subpolar North Atlantic due to the surface buoyancy loss along the northward pathway of the upper AMOC limb.
- Interior mixing, including wintertime convection and warm-season restratification by mesoscale eddies at base of the mixed layer and sub-mixed layer diapycnal mixing, drives upward transformations in the Subtropical Mode Water in the southern part of the subtropical gyre, the Labrador Sea Water on its southward path in the western Newfoundland Basin, and dense Nordic Seas Overflow Waters near the Greenland-Scotland Ridge, and downward transformation of Labrador Sea Water in the Labrador Sea.
- Patterns of upward and downward diapycnal transformations do not align zonally, with strong ribbon-like overturning cells along boundary currents and fronts surrounding downward transformations in convection sites (Figure). Thus, the zonally integrated, two-dimensional representations of the meridional overturning streamfunction underestimate the transformation that takes place three-dimensionally.

**Bibliography**


*Figure:* Horizontal distribution of total diapycnal transformation per unit area (in $10^{-6}$ ms$^{-1}$) across eight density surfaces in the subpolar North Atlantic. Blue color denotes downward (light-to-dense) transformation and is in part due to air-sea buoyancy fluxes. Red color denotes upward transformation and is due to interior mixing.
Signature of the AMOC in the North Atlantic Dynamic Sea Level

PIs: J. Yin\textsuperscript{1}, S. M. Griffies\textsuperscript{2}, S. Zhang\textsuperscript{2,3}\textsuperscript{*}

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\textsuperscript{2}NOAA Geophysical Fluid Dynamics Laboratory
\textsuperscript{3}Ocean University of China

The objectives are to study the influence of the AMOC on dynamic sea level in the North Atlantic and along the east coast of North America, and to detect AMOC variability and change using in situ and remote sea level observations. Throughout this project, we employed the data-model approach, and combined observational data and simulations from a set of state-of-the-art climate models, particularly those developed at GFDL. Our understanding has been deepened about the AMOC-dynamic sea level relationship on interannual, decadal to multi-decadal, and centennial timescales. More specifically, we have made the following achievements during the past four-year period.

**Summary of results from this project (2013-2017)**

We studied sea level rise along the East Coast of the US with the tide gauge data and identified characteristic sea level rise patterns in the north-south direction on different time scales (Yin and Goddard 2013). We established the linkage of these coastal sea level rise patterns with variability modes and forced changes of dynamic sea level in the North Atlantic as simulated by the GFDL ESM2M model. We investigated how the coastal and ocean interior sea level signals are connected to the AMOC variability and change.

We investigated the linkage between a 30\% downturn of the AMOC during 2009–2010 and an extreme sea level rise event along the northeast coast of North America (Goddard et al. 2015; Goddard 2018). We found that in addition to the NAO, the slowdown of the AMOC during 2009–2010 was also an important factor in causing the pronounced coastal sea level spike in 2010 north of New York City. Our analysis suggested that the 2009–2010 AMOC slowdown was very unusual. These results based on sea level observations and model simulations allow us to put the recently observed change of AMOC into context.

To understand the potential impact of Greenland melt on the AMOC and dynamic sea level rise in the North Atlantic, we performed a set of the 21\textsuperscript{st} century projections with the GFDL ESM2Mb model under the RCP4.5 and RCP8.5 emission scenarios (Beadling 2016). This was in collaboration with the AMOCIMP team (Bakker et al. 2016). With more realistic estimates of the meltwater from Greenland, we found that the AMOC weakens slightly further during the 21\textsuperscript{st} century compared with that in the standard RCP projection runs. The additional meltwater also causes a cooling of SST south of Greenland and additional sea level rise around Greenland and on the northeast coast of North America in the 21\textsuperscript{st} century.

We studied the influence of a slowdown/shutdown of the AMOC on the South America monsoon precipitation and the carbon cycle in the Amazon rainforest region (Parsons et al. 2014; Parsons 2017). We performed idealized water-hosing experiments with the GFDL ESM2M model. We found that a moderate weakening of the AMOC can drive small but statistically significant drying in the South American monsoon region. By contrast, a complete shutdown of the AMOC acts to
considerably shift the ITCZ southward, which changes precipitation and carbon cycle patterns over Amazonia.

During the project period, we also participated in and contributed to laboratory- and community-wide research efforts. We have led and contributed to the international CORE-II (Coordinated Ocean-ice Reference Experiments) sea level simulations and analysis (Griffies et al. 2014), and the documentation papers of the GFDL CM3 and CM2.6 models (Griffies et al. 2015).

Bibliography


On the persistence and coherence of subpolar sea surface temperature and salinity anomalies associated with the Atlantic multidecadal variability

Pl: R. Zhang
1NOAA Geophysical Fluid Dynamics Laboratory

The objective of this research is to understand the key mechanisms causing the AMV.

Recent results
This study identifies key features associated with the AMV in both observations and a fully coupled climate model, e.g., decadal persistence of monthly mean subpolar North Atlantic SST and SSS anomalies, and high coherence at low frequency among subpolar North Atlantic SST/SSS, upper ocean heat/salt content, and the AMOC fingerprint. These key AMV features, which can be used to distinguish the AMV mechanism, cannot be explained by the slab ocean model results or the red noise process but are consistent with the ocean dynamics mechanism. This study also shows that at low frequency, the correlation and regression between net surface heat flux and SST anomalies are key indicators of the relative roles of oceanic versus atmospheric forcing in SST anomalies. The oceanic forcing plays a dominant role in the subpolar North Atlantic SST anomalies associated with the AMV.

Bibliography

Figure: Observed and modeled autocorrelations of detrended monthly mean subpolar North Atlantic SST/SSS and subpolar North Atlantic 0-700 m upper ocean heat/salt content (UOHC/UOSC) anomalies. (a) Subpolar North Atlantic SST from slab ocean model GFDL SM2.1. (b,d) Observed subpolar North Atlantic SST/UOHC and subpolar North Atlantic SSS/UOSC. (c,e) Subpolar North Atlantic SST/UOHC and subpolar North Atlantic SSS/UOSC from fully coupled model GFDL CM2.1. Black dash lines: red noise model fitted for GFDL SM2.1 subpolar North Atlantic SST.
Comparison of Mechanisms for Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models

PI: R. Zhang
Collaborators: D. Li, T. Knutson

1NOAA Geophysical Fluid Dynamics Laboratory
2Princeton University

The objective of this research is to investigate the impact of Atlantic low-frequency variability on summer Arctic sea ice extent in three coupled climate models.

Recent results
In this study, the mechanisms for low-frequency variability of summer Arctic sea ice are analyzed using long control simulations from three coupled climate models (GFDL CM2.1, GFDL CM3, and NCAR CESM). Despite different Arctic sea ice mean states, there are many robust features in the response of low-frequency summer Arctic sea ice variability to the Atlantic oceanic heat transport into the Arctic across all three models. In all three models, an enhanced Atlantic heat transport into the Arctic induces summer Arctic sea ice decline and surface warming, especially over the Atlantic sector of the Arctic. There is robust Bjerknes Compensation at low frequency, so that the northward atmospheric heat transport provides a negative feedback to summer Arctic sea ice variations. The response of Arctic sea ice thickness to the Atlantic heat transport is stronger in models that have thicker climatological Arctic sea ice.

Bibliography

Figure: The response of Arctic sea ice to enhanced Atlantic heat transport in three coupled models. (Left) Climatological summer sea ice mass. (Middle) Response of summer sea ice mass to Atlantic heat transport. (Right) Response of summer sea ice concentration to Atlantic heat transport. The response of Arctic sea ice mass increases with mean state sea ice thickness, while the response in sea ice concentration is largest in the model with intermediate mean state sea ice thickness.
On the Discrepancy between Observed and CMIP5 Multi-Model Simulated Barents Sea Winter Sea Ice Decline

PI: R. Zhang¹
Collaborators: D. Li², T. R. Knutson¹
¹NOAA Geophysical Fluid Dynamics Laboratory
²Princeton University

The objective of this research is to investigate the impact of Atlantic low-frequency variability on winter Arctic sea ice extent.

**Recent results**
This study aims to understand the relative roles of external forcing versus internal climate variability in causing the observed Barents Sea winter sea ice extent decline since 1979. We identify major discrepancies in the spatial patterns of winter Northern Hemisphere sea ice concentration trends over the satellite period between observations and CMIP5 multi-model mean externally forced response. The CMIP5 externally forced decline in Barents Sea winter sea ice extent is much weaker than that observed. Across CMIP5 ensemble members, March Barents Sea sea ice extent trends have little correlation with global mean surface air temperature trends but are strongly anti-correlated with trends in Atlantic heat transport across the Barents Sea opening. Further comparison with control simulations from coupled climate models suggests that enhanced Atlantic heat transport across the Barents Sea opening associated with regional internal variability may have played a leading role in the observed decline in winter Barents Sea SIE since 1979.

**Bibliography**

**Figure:** Winter sea ice decline trend in Barents Sea. (Left) Comparison between observed and CMIP5 multi-model external forced trend (1979–2015) in March sea ice concentration. (Right) Trend in March sea ice concentration induced by enhanced Atlantic heat transport associated with internal variability in three coupled models.
Impact of the AMOC on multidecadal variability of Atlantic major hurricane frequency

PI: R. Zhang\textsuperscript{1}  
Collaborators: X. Yan\textsuperscript{2}, T. R. Knutson\textsuperscript{1}  
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\textsuperscript{2}Princeton University

The objective of this research is to investigate the impact of AMOC on multidecadal variability of Atlantic major hurricane frequency.

Recent results
Observed Atlantic major hurricane frequency has exhibited pronounced multidecadal variability since the 1940s. However, the cause of this variability is debated. Using observations and a coupled Earth system model (GFDL-ESM2G), here we show that the decline of the Atlantic major hurricane frequency since 2005 is associated with a weakening of the AMOC inferred from ocean observations. Directly observed North Atlantic sulfate aerosol optical depth has not increased (but shows a modest decline) over this period, suggesting the rapid decline of the Atlantic major hurricane frequency since 2005 is not likely due to recent changes in anthropogenic sulfate aerosols. Instead, we find coherent multidecadal variations involving the inferred AMOC and Atlantic major hurricane frequency, along with indices of AMV and inverted vertical wind shear. Our results provide evidence for an important role of the AMOC in the recent decline of Atlantic major hurricane frequency.

Bibliography

Figure: Observed coherent multidecadal variations among the Atlantic major hurricane frequency, AMOC fingerprint, AMV index, and inverted hurricane shear index.
Appendix D: Bibliography

Bibliography includes only recent paper from 2016-2018.


Appendix E: List of Acronyms

ADCP: Acoustic Doppler Current Profiler
AMO: Atlantic Multidecadal Oscillation
AMOC: Atlantic Meridional Overturning Circulation
AMV: Atlantic Multidecadal Variability
CESM: Community Earth System Model
CESM-LE: Community Earth System Model Large Ensemble
CGFZ: Charlie Gibbs Fracture Zone
CTD: Conductivity/Temperature/Depth
DSOW: Denmark Strait Overflow Water
DWBC: Deep Western Boundary Current
ENSO: El Niño Southern Oscillation
EOF: Empirical Orthogonal Function
Fov: Freshwater transport by AMOC
IPCC: Intergovernmental Panel on Climate Change
IPO: Interdecadal Pacific Oscillation
ISOW: Iceland-Scotland Overflow Water
ITCZ: Inter Tropical Convergence Zone
LIM: Linear Inverse Modeling
MFT: Meridional Freshwater Transport
MHT: Meridional Heat Transport
MOC: Meridional Overturning Circulation
MOCHA: Meridional Overturning Circulation and Heatflux Array
MOVE: Meridional Overturning Variability Experiment
NADW: North Atlantic Deep Water
NAO: North Atlantic Oscillation
NIJ: North Icelandic Jet
OSNAP: Overturning of the Subpolar North Atlantic Program
RAPID: Rapid Climate Change Programme
ROM: Regional Ocean Model
SAMBA: South Atlantic Meridional Overturning Circulation Basin-wide Array at 34.5°S
SAMOC: South Atlantic Meridional Overturning Circulation
SLP: Sea Level Pressure
SPNA: Subpolar North Atlantic
SSH: Sea Surface Height
SST: Sea Surface Temperature
XBT: Expendable Bathythermograph
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