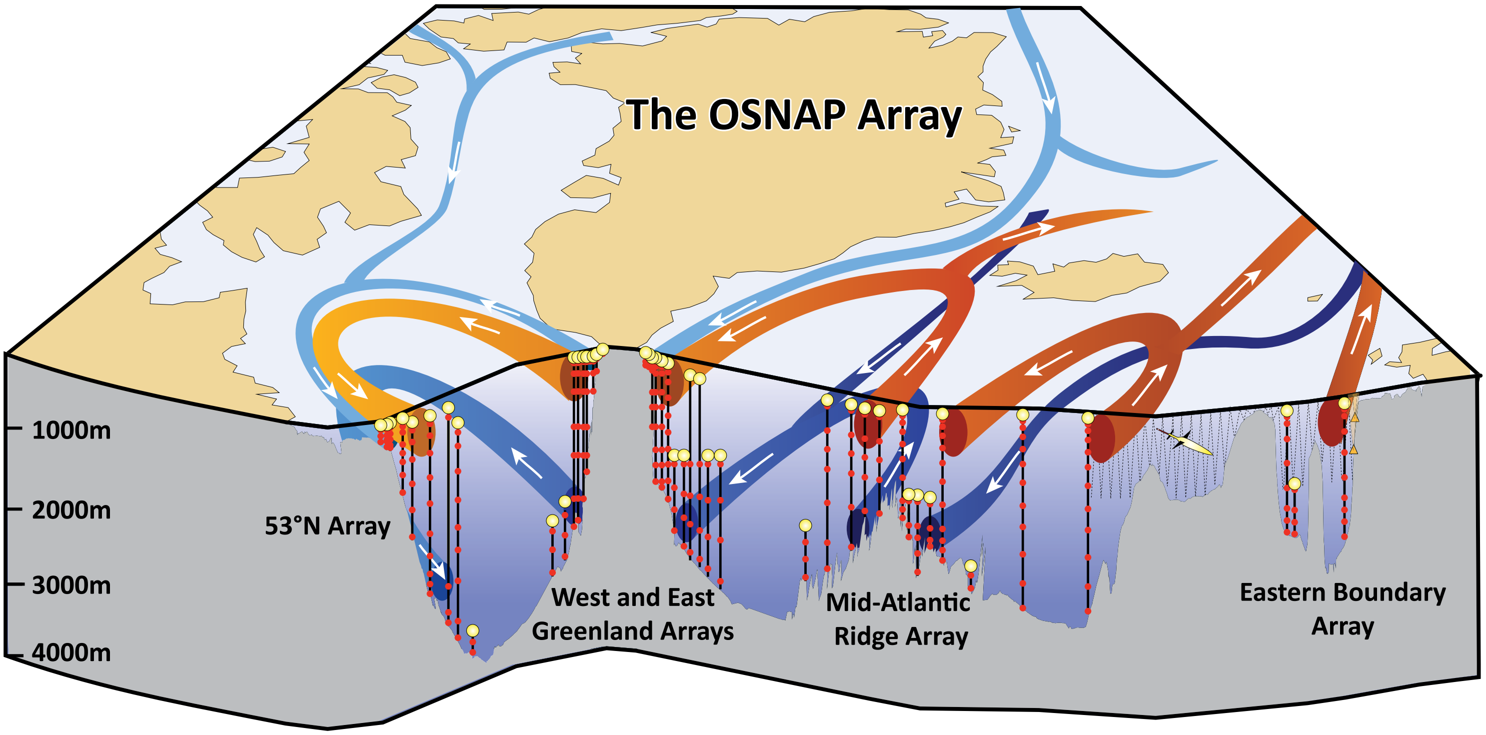

US CLIVAR
Climate Variability & Predictability

2014 US AMOC SCIENCE TEAM ANNUAL REPORT ON PROGRESS AND PRIORITIES

AUTHORS

Gokhan Danabasoglu (Chair)
National Center for Atmospheric Research

Ruth Curry
Woods Hole Oceanographic Institution

Alicia Karspeck
National Center for Atmospheric Research

Chris Meinen
NOAA Atlantic Oceanographic and Meteorological Laboratory

Rym Msadek
NOAA Geophysical Fluid Dynamics Laboratory

Mike Patterson
US CLIVAR Project Office

Renellys Perez
University of Miami/NOAA Atlantic Oceanographic and Meteorological Laboratory

Andreas Schmittner
Oregon State University

Luanne Thompson
University of Washington

Steve Yeager
National Center for Atmospheric Research

EDITOR

Kristan Uhlenbrock
US CLIVAR Project Office

BIBLIOGRAPHIC CITATION

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COVER IMAGE

OSNAP array schematic by Penny Holiday, National Environmental Research Council, UK; OSNAP deployment cruise images from summer 2014 by Amy Bower, Clare Johnson, Karen Wilson, Sijia Zou.

BACK COVER IMAGE

R/V Knorr used for multiple OSNAP cruises during 2014 deployment, image by Sijia Zou.

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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), which was identified as a key near-term priority in the 2007 Ocean Research Priorities Plan issued by the Joint Subcommittee on Ocean Science and Technology (JSOST, now SOST). A five-year implementation strategy for the US AMOC program was developed in October 2007 by a panel of scientists, outlining the program goals and the initial components of an AMOC monitoring system and AMOC prediction capability. A US AMOC Science Team, comprised of funded investigators, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies (NASA, NSF, NOAA, and DOE). The report herein is the seventh annual progress report submitted by the US AMOC Science Team. The purpose of this report is to summarize progress in the past year on the main objectives of the program, identify any programmatic gaps, and make recommendations on both near-term and long-term research priorities and objectives for the program.

Planning activities within the US AMOC program continue to be organized under four Task Teams (TTs), consisting of groups of program principle investigators (PIs), each led by a chair and vice-chair. The TT leaders, together with the Science Team chair, form the US AMOC Program Executive Committee. Following the protocol established in 2013, the TT leaders are selected by the Executive Committee from the nominations provided by the TT members. A list of current leadership positions is as follows:

Science Team Chair: Gokhan Danabasoglu

Task Team 1: AMOC Observing System Implementation and Evaluation
(Chair: Chris Meinen; Vice-chair: Renellys Perez)

Task Team 2: AMOC State, Variability, and Change
(Chair: LuAnne Thompson; Vice-chair: Alicia Karspeck)

Task Team 3: AMOC Mechanisms and Predictability
(Chair: Rym Msadek; Vice-chair: Steve Yeager)

Task Team 4: Climate Sensitivity to AMOC: Climate/Ecosystem Impacts
(Chair: Ruth Curry; Vice-chair: Andreas Schmittner)

The US AMOC Program 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 TTs in helping to coordinate research in these four areas are listed in Appendix A, along with the current membership of each TT.

Meetings of the Science Team have been held annually since 2009. In 2011 and 2013, these meetings were held jointly with the UK RAPID program in Bristol, UK and Baltimore, Maryland, respectively, as joint science conferences. This joint meeting arrangement will continue in the future, with UK RAPID / US AMOC science conferences to be held in 2015 and 2018 and a national Science Team meeting held in intervening years. Following this schedule, the 2014 US AMOC Science Team meeting was held in Seattle, WA during September 9-11, 2014, and the next joint meeting will be held in Bristol, UK on July 21-24, 2015.

As reflected in the TT structure, the US AMOC program has four main objectives:
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; and
4. An assessment of the role of AMOC in global climate and ecosystems.

Progress on these main program objectives during 2014 is summarized in section 2 of this report. A few highlights of the accomplishments of the program during 2014 are listed below:

1. The observational system for monitoring the AMOC was greatly enhanced in the past year with the deployment of a high-latitude North Atlantic observing array (OSNAP: Overturning in the Subpolar North Atlantic Program). This array fulfills an important priority that was identified in the original US AMOC implementation plan – that of measuring the AMOC near the formation regions of the lower limb of the main Atlantic overturning cell. The OSNAP array consists of two legs observing the mouths of the Labrador and Norwegian-Greenland Seas. The array has an initial planned lifetime of four years. Additional key observations in this region are being collected in Davis Strait, Denmark Strait, and across the inflows to the Nordic Seas.
2. The AMOC array at 26.5°N, comprised of the MOCHA and Western Boundary Time Series (WBTS) projects together with the UK RAPID-MOC project, has now collected a decade of fully trans-basin, full-water-column, daily estimates of the volume and heat transports. This data continues to form the backbone of the AMOC observing system and it is routinely used for testing numerical models used in AMOC studies. Other key observations being collected in the subtropical North Atlantic include the lower AMOC branch observations made by the MOVE project, the repeated Gulf Stream sections collected by the Oleander project, and the decade of Deep Western Boundary Current (DWBC) and Gulf Stream measurements collected on Line W.
3. The South Atlantic MOC observing system at 34.5°S, anchored by the SAM project, continues to develop, with major new enhancements to the trans-basin array deployed in 2014 by partners in South Africa and with important contributions continuing from France, Brazil, and Argentina. Several new studies are looking at ways of further enhancing the South Atlantic MOC observing system using satellite gravimetry and/or a combination of satellite and *in situ* data as well as synthesis products and models.
4. The pathways of the lower limb of AMOC have been described in greater detail, including the pathway of North Atlantic Deep Water in the subpolar gyre and through the Charlie-Gibbs Fraction Zone. In addition, the flow of the DWBC, as it travels from the Southwestern Atlantic through to exiting the Atlantic south of Africa, has been described in greater detail using both observations and models.
5. An increased use of satellite products along with Argo data have allowed more detailed examination of the linkages between heat content, heat transport, and AMOC. Comparisons against ocean reanalysis/ state estimate products have facilitated more detailed analysis of the connections between AMOC and the pattern of subsurface warming in the Atlantic Ocean. In addition, AMOC at 26.5°N has been shown to provide an independent metric for evaluation of state estimates.
6. Current reanalysis products show differing AMOC trends over the 20th century. This uncertainty results mainly from the different methodologies used in assimilating the data that constrain the AMOC and

from the lack of robustness of AMOC mechanisms in the models used to derive the reanalysis. Some mechanisms including buoyancy forcing over the Labrador Sea or deep flow interaction with bottom topography appear to be key in controlling the simulated AMOC fluctuations, but their robustness across models remains to be shown. This disparity among the reanalysis products regarding their AMOC trends is not found in forced ocean simulations, which show consistent AMOC variability and trend among each other.

7. An emerging hypothesis regarding synchronization of hemispheric climate subsystems calls for further consideration of mechanisms by which Atlantic Multidecadal Variability signals propagate throughout the Northern Hemisphere. Evidence for a sequence of atmospheric and lagged oceanic teleconnections, labeled the "stadium wave", has spurred several lines of inquiry to develop mechanistic and empirical-dynamical models of this phenomenon, and to determine why it is absent in current generation of general circulation models.
8. AMOC variability exerts an influence on Arctic-sea ice through modulation of ocean heat transport into the Arctic. In the Barents Sea, seasonal sea ice extent has exhibited declining trends that are significantly anti-correlated with Atlantic inflows from 1979 to 2013. Atmospheric circulation and heat transport across the Arctic Circle may have intriguing relationships with AMOC variability, as work with a coupled climate model suggests.

The updated near-term research priorities, long-term research goals and objectives, and associated action items are articulated in section 3. These are updated substantially from last year, following the discussions during the 2014 Annual Science Team meeting in Seattle and through subsequent TT teleconferences. The near-term research priorities include: ensuring that AMOC estimates (and the key underlying measurements collected as part of the AMOC estimates) are being made available in widely recognized locations; improvement to communications between different observing system groups, particularly between more established observing system groups and newer groups becoming involved at the national and international levels; making sure that error estimates are produced and provided alongside AMOC estimates (and the constituent components); providing a more detailed characterization of AMOC flow pathways and their impacts on variability; developing a more comprehensive understanding of the strengths and weaknesses of existing global ocean reanalysis products and hindcasts; quantifying the magnitude, location, and physical mechanisms associated with interior diapycnal mixing in the ocean and evaluating the realism of current ocean GCMs in this regard; investigating the role of freshwater forcing, and south Atlantic freshwater transports, in determining the variability and stability of AMOC; expanding the use of eddy-resolving models in AMOC-related studies; and identifying the mechanisms by which AMOC variability, imprinted on sea surface temperature and/or the cryosphere, affects local and remote atmospheric patterns and phenomena.

For the first time, the annual report contains several long-term priorities for each TT, following the recommendations of the External Review Committee of the US AMOC program. These priorities are intended to reflect what the community would seek to accomplish with unconstrained funding.

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

I Introduction

The Joint Subcommittee on Ocean Science and Technology (JSOST, now SOST) identified the "improved understanding of the mechanisms behind fluctuations of the Atlantic Meridional Overturning Circulation (AMOC), which will lead to new capabilities for monitoring and making predictions of the AMOC changes" as a near-term priority in the Ocean Research Priorities Plan in January 2007. In response to this near-term priority, a panel of scientists developed an implementation plan, released in October of 2007. The five-year implementation plan laid the groundwork for an interagency program to develop the initial components of an AMOC monitoring system and AMOC prediction capability.

In response to this implementation plan, the supporting agencies (NASA, NOAA, and NSF) created a US AMOC Science Team in March of 2008, which has been expanded in subsequent years. In late 2011, DOE was added as a contributing agency, and several new PIs from AMOC-related DOE projects have joined the Science Team. This Science Team, comprised of investigators (PIs, co-Is, post-docs, and students) of funded projects designated by the agency program managers as relevant to the US AMOC program, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies. In October 2012, the US AMOC program completed its fifth year as a SOST priority and provided a final report on the achievements and remaining challenges in advancing the understanding of the AMOC. The four sponsoring agencies confirmed their commitment to continue forward with the US AMOC Science Team within US CLIVAR in order to fulfill the goals of the program.

As one of its responsibilities, the Science Team produces annual 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 2014 US AMOC Science Team Meeting, hosted by the University of Washington, was held in Seattle during 9-11 September 2014, The scientific organizing committee was chaired by LuAnne Thompson (University of Washington) with members including Gokhan Danabasoglu (NCAR), Yochanan Kushnir (LDEO), Chris Meinen (NOAA/AOML), Weijer Wilbert (LANL), Steve Yeager (NCAR), Mike Patterson (US CLIVAR), Jill Reisdorf (UCAR JOSS), and Kristan Uhlenbrock (US CLIVAR). The meeting was well attended with over 80 participants, including Science Team members, local scientists and students, additional interested scientists and students from within and outside the US, and sponsoring agency managers. The meeting focused on four objectives: i) evaluation and implementation of observational efforts; ii) estimates of AMOC state, variability, and change; iii) understanding mechanisms of variability and the potential for predictability of AMOC; and iv) the impacts of AMOC changes on climate, cryosphere, regional sea level, ocean carbon-biogeochemistry, and marine ecosystems. Lively and broad discussions during the breakout sessions covered the near- and long-term research priorities and objectives for the program as well as possible new collaboration opportunities. A meeting summary, prepared by LuAnne Thompson, Gokhan Danabasoglu, and Mike Patterson, was released in *Eos* (Thompson et al. 2015). Meeting presentations are available at http://usclivar.org/meetings/2014-us-amoc-science-team-meeting-agenda.

The next meeting is a joint UK RAPID / US AMOC Science Conference to be held in Bristol, UK on July 21-24, 2015. It will bring together scientists internationally in a conference-style meeting to share research findings on four scientific themes: i) characterizing the structure, variability, mechanisms, and oceanic response; ii) impacts of AMOC on the atmosphere, cryosphere, and land; iii) AMOC state estimation, predictability, and prediction; and iv) novel approaches to pan-Atlantic observations, modeling, analysis, and synthesis. Renellys Perez (NOAA/AOML), Steve Yeager (NCAR), and Rong Zhang (NOAA/GFDL) are the US members of the organizing committee – along with UK members Meric Srokosz, David Smeed, Penny Holliday (all three of the National Oceanographic Centre), and Rowan Sutton (University of Reading).

Following recommendations from the 2012-2013 External Review Report (Talley et al. 2013), US AMOC promoted the science and programmatic opportunities at the 2014 AGU Fall Meeting in San Francisco. Science Team members, Alexey Federov (Yale University) and LuAnne Thompson (University of Washington), along with Jerry McManus (Columbia University) and Eleanor Frajka-Williams (UK National Oceanographic Centre), co-convened AMOC sessions with 16 oral and 27 poster presentations addressing the understanding of AMOC variations across timescales and its linkages with climate, including studies of both modern and paleo records. The US CLIVAR Project Office presented a poster outlining the US AMOC program and opportunities for interested scientists, particularly those from other communities, to participate in the program.

The report herein is the seventh annual report submitted by the US AMOC Science Team. This report describes the progress made in the four major areas of focus within the program during 2014, followed by a significantly updated set of near-term research priorities as well as longer-term program objectives based on the discussions that occurred during the 2014 Science Team Meeting and during the recent TT teleconferences.

2 PROGRESS ON PROGRAM OBJECTIVES

2.1 Existing and approved observatonal projects

Characterizing and understanding the variability of the basin-wide Atlantic Ocean circulation remain ongoing challenges for the AMOC community and are prerequisites for skillful seasonal to inter-annual (or even decadal) climate prediction. Various elements of a basin-wide AMOC observing system have been in place for several years, and during the past year several important enhancements of the system have been initiated. Grouped according their geographical regions, this section summarizes the existing observational projects collecting AMOC-relevant measurements and discusses some of the recent results obtained from those projects that are helping to improve our understanding of the complex AMOC system.

2.1.1 Subtropical North Atlantic

Several projects continue to be tasked with continuous monitoring of the strength and structure of the AMOC and its associated heat and/or salt transports in the North Atlantic subtropical region:

- The “Western Boundary Time Series (WBTS)” project (*Baringer, Meinen, and Garzoli*). The project has been monitoring the warm, northward flowing Florida Current and the cold, southward flowing Deep Western Boundary Current (DWBC) nearly continuously since 1982, using a combination of submarine cable, moored instrument, and hydrographic observations.
- “Measuring interannual variability of the AMOC and meridional ocean heat transport at 26.5°N: The RAPID-MOCHA Array” (*Johns, Meinen, and Baringer*). The program has collected a decade (since 2004) of meridional volume and heat transport estimates through its contributions to the joint UK-US trans-basin array of 22 moorings deployed at 26.5°N together with the Florida Current cable observations.
- “The Oleander Project: Sustained observations of ocean currents in the Northwest Atlantic between New York and Bermuda” (*Donohue, Flagg, and Rossby*). The project has collected weekly ADCP and monthly XBT measurements since 1992 from container vessel CMV Oleander, which operates on a weekly schedule between New Jersey and Bermuda.
- “Meridional Overturning Variability Experiment (MOVE)” (*Send and Lankhorst*). The project has collected more than a decade of data on the lower branch of the AMOC at 16°N, using a system of moored instruments between the western boundary and the Mid-Atlantic ridge.
- “Line W: A sustained measurement program sampling the North Atlantic DWBC and Gulf Stream at 39°N” (*Toole, Andres, Curry, Joyce, McCartney, and Smethie, Jr.*). The program completed a 10-year observing program studying inter-annual transport changes in the North Atlantic’s DWBC and Gulf Stream at 39°N, using data from a sustained moored array and repeated occupation of a hydrographic section.

The combined datasets of the 26.5°N array (from the WBTS, MOCHA, and UK RAPID-MOC projects) suggest a weak but statistically significant downward trend in the AMOC from the first 8.5 years of the joint array (Smeed et al. 2014). This change is likely to be associated with inter-annual and/or decadal variability, and it is superimposed on top of much stronger subannual variations that make extracting trends difficult. Western boundary flow variability in the lower limb of the AMOC at 26.5°N has been shown to be strongly influenced by westward propagating features that mask the DWBC signals: an important issue for AMOC monitoring (Meinen and Garzoli 2014). Significant effort in the past year was aimed at carefully analyzing and increasing the measurement accuracy of AMOC volume and heat transport measurements and key components of the system (e.g., Garcia and Meinen 2014; McCarthy et al. 2015). Comparison of observations at 26.5°N with numerical models of varying complexity indicates that most of the observed inter-annual variability in the AMOC that is not related to Ekman transport appears to be linked to wind-forced mid-ocean variability associated with first baroclinic mode Rossby waves. These waves are excited by interannual wind stress curl anomalies in the central and western part of the basin (Zhao and Johns 2014a; b).

At 37°N, the Oleander data continues to show a rather stable Gulf Stream transport over the past two decades (Rossby et al. 2014). Comparison with the continuous transport observations in the Florida Straits indicates little correspondence between Gulf Stream volume transport fluctuations at 27°N and 37°N (Sanchez-Franks et al. 2015), illustrating the complexity of the AMOC upper limb.

2.1.2 Subpolar North Atlantic and Arctic

The hydrography and circulation in Arctic and subarctic regions and their relationships with the AMOC are being observed by the following projects:

- "The Arctic Observing Network: Sustained observations at the Davis Strait gateway" (*Lee, Gobat, and Stafford*). The project continues to monitor the flow through a key Atlantic-Arctic exchange pathway, using a combination of moorings and gliders.
- "OSNAP: Overturning in the Subpolar North Atlantic program" (*Lozier, Johns, Bower, Pickart, and Straneo*). This is a newly implemented project that will provide a continuous record of the full water column, trans-basin fluxes of heat, mass, and freshwater in the high-latitude subpolar North Atlantic, using fixed current meter arrays, repeat hydrographic occupations, RAFOS float deployments, and glider surveys. The arrays and Lagrangian floats were deployed in summer 2014 along two tracks: 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 first data-retrieval is expected in summer 2015, although data from the full array will not be recovered until summer 2016; most of the RAFOS floats will also first surface in 2016.
- "The Norröna Section" (*Rossby and Flagg*). The project has collected more than five years of data on the strength and structure of the Atlantic inflow into the Nordic Seas between Scotland, the Faroes, and Iceland via ADCP measurements on the ferry MF Norröna.
- Pathways to the Denmark Strait overflow: A Lagrangian study in the Iceland Sea (*de Jong and Bower*). This is a new project that has started to quantify the early pathways of the waters that will become the cold deep limb of the AMOC by looking upstream of the overflow region in the Denmark Straits.

Observations at Davis Strait show weak seasonality and significant inter-annual variability in volume and freshwater transports, with no clear trends observed between 2004-2013 (Curry et al. 2014). Continued measurements with improved coverage of the flow in the Faroe-Shetland Channel and over the Iceland-Faroe Ridge suggest that historical circulation estimates of inflow over these key regions were both off by about 1 Sv (Childers et al. 2014).

2.1.3 South Atlantic

The South Atlantic circulation associated with the AMOC is being observed and studied by these projects:

- "Southwest Atlantic MOC project (SAM)" (*Meinen, Garzoli, Perez, and Dong*). This project is designed to measure both the warm-upper and cold-deeper flows associated with AMOC near the western boundary at 34.5°S. The array has now collected more than 5 years of data and will last through 2016. Additional deployments by international partners in Brazil, France, and South Africa have led to the development of a complete trans-basin array at 34.5°S during 2014 – known as the South Atlantic MOC Basin-wide Array ("SAMBA").
- "Variability of the South Atlantic Meridional Overturning Circulation" (*Landerer, Bentel, Boening, and Zlotnicki*). This is a new project looking at methods to measure the AMOC using satellite gravimetry.
- "Variability of the South Atlantic Subtropical Gyre" (*R. Perez*). This new project aims to better quantify the relationship between the South Atlantic subtropical gyre and the AMOC, using a combination of satellite and *in situ* data as well as synthesis products and numerical models.

The SAM array results, analyzed in concert with observations from parallel international projects, show a highly variable AMOC at 34.5°S with a daily accuracy of 5.9 Sv (Meinen et al. 2013). This accuracy will greatly improve with the new observing systems deployed by international partners between 2012 and 2014 (e.g., Ansorge et al. 2014). Argo data from the South Atlantic region has been compared to several modern coupled numerical climate models to illustrate issues in the model representation of the seasonal density variations near the eastern and western boundaries at 34.5°S (Dong et al. 2014).

2.1.4 Relationships with other observing system and modeling programs

A key consideration when evaluating the effectiveness of the AMOC observing system is the dependence of the individual projects on both international partners and on the backbone systems of the Global Ocean Observing system. Many of the projects discussed above depend on international partners, with the United Kingdom playing a critical role at 26.5°N; Canada, Germany, the Netherlands, and the United Kingdom playing key roles in OSNAP near 55°N; and Argentina, Brazil, France, and South Africa playing key roles at 34.5°S. Furthermore, additional projects by international researchers are making (and will continue to make) important contributions, such as the new AMOC array deployed by Germany at 11°S. Beyond these direct participations in the AMOC observing systems, the international community also plays key roles in the Global Ocean Observing System, parts of which are crucial to the success of the US AMOC observing system. Examples include, but are not limited to, satellite observations (e.g., altimetry, gravimetry) and hydrographic observations (e.g., repeat CTD and/or XBT sections, the Argo float system). The US AMOC community is strongly supportive of the Global Ocean Observing System as well as of the crucial contributions made by our international partners in the study of the AMOC.

Prognostic models will also continue to provide many important insights into AMOC (e.g., Danabasoglu et al. 2014). Continued development of formal model-data synthesis techniques will help provide a baseline for the use of the existing global observing system, consisting of full suite of satellite data and *in situ* data to produce valuable ocean state estimates. Future advances in AMOC observing systems and methods will depend on improvements in numerical modeling and analysis, and observations of the AMOC cannot be considered as independent of important advances in these areas.

2.1.5 Data repositories

Quality-controlled observational data collected by the US AMOC projects are made available for community-wide access through the many project-maintained websites enumerated below:

NOAA Florida Current (FC) and cruise data: http://www.aoml.noaa.gov/phod/wbts/data.php
FC and cruise data merged with MOC data: http://www.noc.soton.ac.uk/rapidmoc/
FC and cruise data merged with Heat transport data: http://www.rsmas.miami.edu/users/mocha/
Oleander website: http://po.msrc.sunysb.edu/Oleander
Oleander data distribution: http://www.po.gso.uri.edu/rafos/research/ole
Line W: http://www.whoi.edu/science/PO/linew/index.htm
US Cooperative Arctic Data and Information Service (CADIS): http://www.aoncadis.org
NOAA instruments for SAM: http://www.aoml.noaa.gov/phod/research/moc/samoc
Norröna section data archive: http://po.msrc.sunysb.edu/Norrona/
MOVE array data website: http://mooring.ucsd.edu/projects/move/move_intro.html

2.2 Evaluation of AMOC state, variability, and change

The US AMOC Program supports efforts to assess the past and current state of AMOC, including its variability and linkages between AMOC and other aspects of climate variability and change. A variety of tools are used to do this, including analysis of observations, numerical models of both past and future changes in the ocean, as well as state estimation/data assimilation. Many of the efforts integrate different techniques and approaches, including combining models with observations. Investigating observationally constrained modes of variability, transport pathways and linkages to other ocean basins, and linkages to the atmosphere through heat transport and uptake is essential for evaluating the role of the Atlantic Ocean for improving seasonal to inter-annual (or even decadal) climate prediction.

2.2.1 Transport pathways associated with the AMOC

A series of observational and modeling efforts are working towards a more refined understanding of the pathways of the deep to intermediate circulation and the connection to AMOC as well as the connection between the North Atlantic and the higher latitudes:

- "Crossroads of the Atlantic meridional overturning circulation: the Charlie-Gibbs Fracture Zone (CGFZ)" (*Bower and Spall)*. This project is a combined observational and modeling study of the flow through the CGFZ. It includes a model investigation of the impact of an idealized version of the CGFZ on the western boundary current.
- "The Dynamics of Abyssal Mixing and Interior Transports Experiment (DynAMITE)" (*Curry and Polzin*). This field program consists of a set of moored instruments deployed between Bermuda and the Mid-Atlantic Ridge to investigate both diapycnal mixing and circulation. The focus is on the pathways of the transformation of the densest water into warmer and lighter water masses.
- "The Atlantic water boundary current in the Eastern Arctic: Composition, transport, variability, and dynamics" (*Pickart*). Eight moorings in the Eastern Arctic have been recently deployed to observe and understand the Atlantic water boundary current over an annual cycle.
- "Analysis of eddies, mixing and denser overflows of meridional circulation in the climate system" (*Rhines and Eriksen*). This analysis of observations taken by gliders between Iceland and Norway and in the

Labrador Sea is allowing a new evaluation of the flow of Atlantic water into the Nordic Seas as well as the dense overflows at the Iceland-Faroe Ridge.

- "South Atlantic meridional overturning circulation: Pathways and modes of variability" (*Perez, Garzoli, and Matano*). This project is using multiple modeling approaches to understand the pathways of the upper and lower limbs of the AMOC in the South Atlantic, including the fate of the DWBC in the South Atlantic.
- "Transport in the upper branch of the South Atlantic meridional overturning circulation" (*Schmid and Halliwell*). This work combines multiple data sources to estimate the three dimensional absolute velocity fields in the South Atlantic to derive seasonal estimates of volume transports of the upper limb of AMOC.

AMOC reflects the zonally integrated circulation but hides the spatial pathways of fluid parcels. For a more complete understanding of what controls both the mean AMOC and its variability, it is important to gain insight into how different parts of the water column contribute to the meridional transport of fluid. High resolution modeling of Xu et al. (2014) shows the details of the pathways of the dense NADW into the subpolar gyre. Recent observational efforts have begun to elucidate the pathways of the deep flow through CGFZ in the North Atlantic (Furey et al. 2014), and modeling work is being used to connect this topographically constrained flow with the western boundary current.

An analysis of historical and new hydrographic data (including CFC measurements) along with numerical modeling experiments suggests that the flow of the DWBC in the South Atlantic is quite complicated, with multiple branches south of 20°S all eventually exiting the Atlantic south of South Africa (Garzoli et al. 2015). A nested model with high-resolution grid refinement in the Southwestern Atlantic (Combes and Matano 2014) has produced new insights into the structure of the salinity field in the region (Matano et al. 2014), and validation of the model has been made using satellite observations (Guerrero et al. 2014). This model is being used to study AMOC water mass pathways in the South Atlantic.

2.2.2 Sources and implications of variability of AMOC

Modeling and observational approaches are being used to understand all aspects of variability of AMOC, both by quantifying changes and investigating how and why they occur on all times scales and by connecting the variability with changes in other properties of the Atlantic climate. This includes linkages with the atmosphere, oceanic heat content and transport, and salinity of the Arctic Ocean. The related studies are as follows:

- "State of the climate: Quarterly reports on the meridional heat transport in the Atlantic Ocean" (*Baringer, Garzoli, and Goni*). This project is focused on estimating heat transport variability in the subtropical gyres in both the North and South Atlantic using XBT, satellite data, state estimates, and climate models.
- "Using ocean data assimilation to explore Arctic/Subarctic climate variability" (*Carton, Chepurin, Häkkinen, and Steele*). This project is focused on both the development of the Simple Ocean Data Assimilation (SODA) reanalysis and analysis of the connection between AMOC and salinity in the Arctic Ocean using the CMIP5 models.
- "On the evolution of the AMOC fingerprint in the North Atlantic" (*Zhang and Zhang*). This project uses targeted model experiments to investigate how a perturbation of AMOC in the subpolar region leads to changes in the subtropical region at a later time.
- "Forced transients in water mass transformation and the meridional overturning" (*Spall*). Using simplified models, this project is focused on developing insight into how and why AMOC and associated water mass transformation respond to changes in atmospheric forcing.

- "Satellite multi-sensor studies of deep ocean convection in the North Atlantic Ocean" (*Yan and Jo*). This project uses satellite sea level, Argo data, and analysis of numerical model output to investigate the relationships between heat content in the subpolar gyre, deep convection in the Labrador Sea, and AMOC.
- "Improved estimates of AMOC and global meridional circulation using altimetry with *in situ* tracers" (*Rhines and Hakkinen*). Analysis of reanalyses products and direct observations of warming in the North Atlantic Ocean are performed to determine the spatial patterns of warming. In addition, an analysis of the depth and density dependence of the heating is performed.
- "Sources and impacts of variability of the meridional property transport in the Atlantic Ocean" (*Kelly and Thompson*). This study uses a simple data constrained model as well as analysis of the relationship between sea level as a proxy for upper ocean heat content and surface heat fluxes to investigate the variability in the basin wide meridional heat transport and exchange of heat with the atmosphere.
- "Meridional variability of the South Atlantic meridional overturning circulation" (*Goni and Dong*). This project is using satellite sea level combined with synthetic temperature and salinity profiles to estimate AMOC and MHT between 20°S and 34.5°S.
- "Wave processes along 26°N in the Atlantic" (*Szuts and Martini*). This project is an analysis of wave motions at all time scale in the 26°N mooring observations with a focus on the western boundary moorings and what controls the variability there.

Progress on the evaluation of AMOC state and associated heat transport is being made by combining multiple observational perspectives and models. By combining information from observations and models, Dong et al. (2014) show that the geostrophic transport plays an equal role to the Ekman transport in the AMOC seasonal variations at 34°S. This is different from the predominant control of the Ekman transport on the AMOC seasonality in the coupled climate models in the South Atlantic. Baringer et al. (2014) reexamine the South Atlantic AMOC time series and compare it to the ECCO2 State estimation model, showing that the modeled state estimation for the period 2002-2014 does not correlate well with observations at 35°S (based on XBTs), while it does correlate strongly with observations at 26°N (from the RAPID-MOCHA array) and 41°N (from Argo and altimetry). Satellite observations of sea surface height, mass, *in situ* based estimates of heat storage, and observationally constrained surface fluxes have been used to develop an estimate of meridional heat transport (MHT) at multiple latitudes in the Atlantic (Kelly et al. 2014). This study finds that the MHT variability is coherent from the South Atlantic through to the Gulf Stream. In a joint analysis of a set of six state-of-the art ocean reanalysis products, Karspeck et al. (2014) argue that there is no consensus in the year-to-year variability or long-term trends in AMOC over the last 50 years. Collaborative work with the ocean data assimilation community is ongoing to determine the reasons for discrepancies between the transport properties in ocean synthesis products.

The links between atmospheric forcing and the state of the North Atlantic Ocean are also being investigated via modeling and observations. Using altimetry-based sea surface height estimates, Li et al (2014) show that the subpolar gyre changes are dominated by decadal and longer term changes, and they suggest that these changes may be linked to changes in AMOC. The dominant modes of variability in the temperature and ocean heat content of the central Labrador Sea are examined using Argo float data by Li et al. (2015). Inter-annual signals are closely correlated to the variability of deep convection in the Labrador Sea, and this variability is linked to the cumulative North Atlantic Oscillation (NAO) index. Yasuda and Spall (2014) show that the dependence of the convection and overturning on forcing by precipitation in an idealized model depends critically on the frequency of the precipitation anomalies. Hakkinen et al. (2015) show that from the 1950s to 2012 the energy gain in the upper 2000m in the North Atlantic is about 30% of the global ocean warming over this period and that isopycnal layer heat content varies mostly through layer thickness and lateral extent (through heat transport convergence, rather than variability of temperature/salinity 'spice').

2.3 Assessment of AMOC variability, mechanisms, and predictability

The projects related to AMOC variability mechanisms and predictability share common goals of improving our understanding of the fundamental physical processes, both internal to the ocean and involving coupled interactions, which give rise to AMOC variability; and assessing the extent to which AMOC variations and related climate impacts can be predicted in advance. Ocean models are key tools employed by most projects in pursuit of mechanistic understanding, and these span the spectrum from simple idealized or linear models to regional ocean models to complex coupled general circulation models.

2.3.1 AMOC variability mechanisms

Investigation of the mechanisms of AMOC variability in coupled models, ocean – sea ice forced experiments, reanalysis, and state estimates continues to be the focus of a number of projects:

- "Identifying mechanisms of AMOC variability in ECCO state estimates and CMIP5 models" (*Buckley, Heimbach, Ponte, and Furtado*).
- "Sensitivity patterns of Atlantic meridional overturning and related climate diagnostics over the instrumental period" (*Ponte and Heimbach*).
- "Understanding changes in the Atlantic meridional overturning circulation during the 20th century using IPCC AR5 model ensembles" (*Chang, Yeager, and Danabasoglu*).
- "A collaborative multi-model study: understanding AMOC variability mechanisms and their impacts on decadal prediction" (*Danabasoglu, Yeager, Karspeck, Tribbia, Delworth, Msadek, Rosati, Kwon, and Frankignoul*).

Two projects led by *Ponte and Buckley*, respectively, examine the relative contributions of atmospheric forcing and ocean dynamics (AMOC) to upper ocean heat content (UOHC) variability. Using the ECCO state estimate (1992-2011), Buckley et al. (2014; 2015) find that active ocean dynamics (including ocean heat transport convergence due to AMOC variability) are important determinants of UOHC in the Gulf Stream region and the subpolar gyre, at least on monthly and inter-annual time scales. This contrasts with the interior subtropical gyre where local atmospheric forcing (i.e., heat fluxes plus Ekman transport) explains a majority of UOHC variability. The physical processes of AMOC variability are also being investigated as part of two collaborative projects between NCAR, GFDL, WHOI, and SUNY led by *Danabasoglu* (see section 2.3.3 for the second project). Buoyancy forcing over the Labrador Sea and deep flow interaction with bottom topography are highlighted as key processes in controlling AMOC variability as reported by Yeager and Danabasoglu (2014) and Yeager (2015). The relevance of AMOC variability to our ability to make decadal climate predictions is also being pursued. The usefulness of AMOC representation in density and depth space for predicting Atlantic MHT is compared by Kwon and Frankignoul (2014), who show that while AMOC in density space might better reflect the physical changes in the subpolar gyre, AMOC in depth space can provide some predictive skill for Atlantic MHT. Understanding AMOC fluctuations during the 20th century is being further addressed by the *Chang et al.* project. Their analysis shows that the driving mechanism of the Atlantic Multidecadal Variability (AMV) is different in the CESM Large Ensemble simulations and in the forced ocean experiments. Heat flux is dominant in the former, whereas the AMOC is the main driver in the latter. The better correspondence of the late 20th century sea surface temperature (SST) warming with observations in the forced experiments suggests that the mechanism at work in the CESM Large Ensemble is not realistic.

2.3.2 Sensitivity of AMOC to changes in the climate system

The AMOC sensitivity to changes in a specific component of the climate system is explored by five projects:

- "High-resolution model development to quantify the impact of icebergs on the stability of the AMOC" (*Condron and Bradley*).
- "Effects of the Bering Strait closure on AMOC and global climate under different background climates" (*Hu*).
- "Modeling effects of Greenland Ice Sheet (GIS) melting on AMOC variability and predictability" (*Schmittner, Hu, and Mernhild*).
- "Relationship of the Atlantic Warm Pool with the AMOC and link of the AMOC with global climate model biases" (*Wang*).
- "Role of atmospheric internal variability in the Atlantic meridional overturning circulation" (*Chang and Kirtman*).

Condron and Bradley quantifies the impact of icebergs on the stability of the AMOC using a high-resolution version of the MIT general circulation model (at about 1/6^{o} horizontal resolution) coupled to an iceberg model. A simulation of the last ice age indicates that icebergs and melt water discharged from the Laurentide ice during glacial times would have been first transported to the subtropical gyre by narrow coastal boundary currents and then to the subpolar gyre by the Gulf Stream. As a result of this subtropical pathway, the response of the NADW formation to increased freshwater forcing at high latitudes is muted compared to the more traditional freshwater hosing experiments. Further work by *Schmittner and collaborators* is aimed at quantifying the effects of GIS melting on AMOC variability and predictability. For that purpose, a parameterization of future GIS melt has been developed and implemented in climate change simulations of several coupled models, and its effect on the circulation will be assessed. Testing the effect of closing Bering Strait on AMOC fluctuations under different climate conditions, *Hu and collaborators* find a robust AMOC intensification, an associated increase in northward meridional heat transport, and a reduced sea ice export and less fresh water in the North Atlantic in all their experiments. *Chang and Kirtman* explore the role of atmospheric internal variability in AMOC fluctuations. They show that extreme flux events occur more frequently during a positive phase of the East Atlantic Pattern. The impacts on the AMOC are currently being investigated. Another mechanism being tested in a project led by *Wang* is related to the influence of temperature and salinity anomalies in the Atlantic warm pool on AMOC variability. Three papers document the results of this analysis, Zhang et al. (2014a; 2014b) and Wang et al. (2014).

2.3.3 AMOC and predictability

Two projects are particularly focused on the predictability of AMOC variability:

- "Initial value predictability of intrinsic modes and implications for decadal prediction over North America" (*Branstator, Teng, Meehl, and Gritsun*).
- "Collaborative research EaSM2: Mechanisms, predictability, prediction, and regional and societal impacts of decadal climate variability" (*Danabasoglu, Anderson, Branstator, Lindsay, Tribbia, Frankignoul, Kwon, Zhang, Yeager, Karspeck, Long, Jiang, and Teng*).

Branstator and collaborators pursue work on initial value predictability that show that AMOC and North Atlantic heat content anomalies are predictable for about a decade in initialized coupled model experiments.

Using tools borrowed from statistical physics, they identify the most efficient distribution of fluxes that produce a large AMOC circulation and find that the pattern is very similar to the leading EOF of AMOC anomalies in the version of CCSM4 they analyze. A novel result is that forcing by the atmosphere might be involved in the initiation of highly predictable AMOC anomalies. *Danabasoglu and collaborators* show that the preferred timescale of AMOC variability is not robust across simulations when the physics is perturbed or the atmospheric initial conditions are changed. They highlight, however, some robust aspects of AMOC variability, such as the influence of deep water formation in the Labrador Sea region on AMOC strengthening, and its forcing by atmospheric variability. Idealized experiments where the NAO forcing is added to the GFDL CM2.1 coupled model fluxes suggest that the AMOC response is sensitive to the time scale of the NAO, with substantial responses only for timescales comparable to or longer than the dominant mode of internal AMOC variability of the model (Delworth et al. 2015).

The predictive capabilities resulting from AMOC variability are investigated by NCAR scientists who extend earlier work by Yeager et al. (2012) on the prediction of the mid 90's subpolar North Atlantic warming. They analyze Community Earth System Model (CESM) forecasts initialized every year between 1955 and 2014 and find high skill in predicting the propagation of anomalies in the Labrador sea that govern the oceanic heat transport into the subpolar North Atlantic. This leads to high skill in predicting subpolar gyre SST and sea ice extent in the North Atlantic sector of the Arctic (Yeager et al. 2015). Predictive capabilities for ocean ecosystems and biogeochemistry are also being investigated by this group focusing on the potential predictability of the Gulf Stream latitude and its implications for the prediction of fish distribution in the US Northeast shelf. Another focus of the *Danabasoglu and collaborators* project is on the feedbacks between AMOC variability and atmospheric circulation. A negative NAO-like pattern driven by a meridional SST dipole is identified in response to an intensification of the AMOC in the Community Climate System Model version 4 (CCSM4). Additional work is ongoing to assess the link between North Atlantic decadal variability and weather extremes, and more specifically North Atlantic winter-time cyclones.

2.3.4 AMOC stability

Theoretical investigations of AMOC stability and optimal excitation continue to be pursued using simplified models and linear theory:

- "Multiple equilibria and low-frequency variability in the adiabatic overturning circulation" (*Cessi and Wolfe*).
- "A generalized stability analysis of the AMOC in Earth System Models: Implication for decadal variability and abrupt climate change" (*Fedorov and Sevellec*).
- "A linear stochastic analysis of model diversity in AMOC dynamics" (*Penland, MacMartin, McColl, Zanna, Hartten, and Tziperman*).

Cessi and Wolfe extend their earlier work in which they identify a positive salt feedback at work in the adiabatic pole-to-pole overturning (Wolfe and Cessi 2014a), by introducing asymmetries in the salt forcing which give rise to multiple equilibria. Transitions between multiple AMOC regimes are explored in a forthcoming paper (Wolfe and Cessi 2014b). *Fedorov and Sevellec* recently published several papers in which generalized stability analysis is used to shed light on decadal (Sevellec and Federov 2013a; 2013b; 2014a) as well as millennial (Sevellec and Federov 2014b) variations in AMOC strength. *Penland and colleagues* recently presented results showing that linear statistical techniques can be used to characterize and interpret salient differences in the AMOC variability mechanisms obtained in IPCC-class coupled GCMs.

2.3.5 Role of high latitude processes in AMOC variability

Finally, a growing number of projects are focused on the role of high latitude shelf and overflow waters in AMOC variability:

- "Denmark Strait overflow water: Western Boundary Current" (*Pickart and Spall*).
- "The upstream sources of the Denmark Strait Overflow" (*Harden and Pickart*).
- "Mechanisms of freshwater exchange across the East Greenland Shelf" (*Spall and Haine*).

The *Pickart and Spall* project resulted in numerous studies examining the origin, pathways, and transports of the source waters of the Denmark Strait Overflow Water (DSOW). They recently found that while total overflow transport remains constant throughout the year, the fraction of Atlantic-origin water versus Arctic-origin water varies considerably in time. Their most recent publications relate to air-sea exchange and convection in the Labrador and Nordic Seas, under-ice blooms in the Arctic Ocean, and topographic influences on western boundary currents. A new project led by *Harden and Pickart* continues the investigation of DSOW variability and its relation to the distinct upstream transports associated with the East Greenland Current (EGC), the separated EGC, and the North Icelandic Jet. *Spall and Haine* started a new project aimed at elucidating the mechanisms that control freshwater exchange between the EGC and the interior of the subpolar and Nordic Seas. This is a key factor in AMOC variability insofar as it determines surface buoyancy conditions in the primary deep water formation regions.

2.4 Climate sensitivity to AMOC: Climate-ecosystem impacts

In addition to the goals covered by the other three TTs, the US AMOC program aims to significantly improve understanding of the degree to which AMOC variability influences other components of the Earth system – locally or remotely – including physical processes in the atmosphere and cryosphere, changes in sea level, biogeochemical cycling in the ocean, and the dynamics of marine ecosystems. Active research projects associated with the TT4 objective of assessing sensitivity to AMOC variability address a broad range of topics, which are interconnected on multiple levels (e.g., ocean – atmosphere – cryosphere interactions), and in some cases, closely linked to other TT objectives (e.g., understanding AMOC mechanisms, fingerprints, and its future state). The specific projects are:

- "The contributions of ocean circulation to North Atlantic SST" (*Kelly and Dickinson*). The project investigates the relative importance of surface fluxes and ocean circulation to generating SST anomalies that underlie large-scale patterns such as the AMV.
- "Influence of the equatorial Atlantic cold tongue and Angola Current on Atlantic Basin climate variability" (*Vizy and Cook*). The study utilizes satellite observations, reanalyses, and models to investigate the degree to which tropical and subtropical ocean-atmosphere interactions in the eastern South Atlantic influence local and remote Atlantic variability.
- "Assessing unstoppable change: Ocean heat storage and Antarctic glacial ice melt" (*Gille and Martinson*). The project applies a variety of observational datasets (Argo floats, altimetry, hydrography, and Antarctica's Long Term Ecological Record, LTER) to evaluate meridional overturning in the South Pacific and contributing factors.
- "An interactive multi-model for consensus on climate change" (*Duane, Tsonis, Kocarev, and Tribbia*). The project investigates coupling between observed regional climate modes (reflected by indices such as the

AMV, PDO, NAO, ENSO) in order to develop parameterizations of coupled delayed oscillating systems.

- "Decadal variability of interacting climate subsystems in the Northern Hemisphere" (*Kravtsov and Tsonis*). Similar to the project above, this study investigates the interplay of decadal climate modes and teleconnections using atmospheric reanalyses, GFDL CM3, and other CMIP5 simulations.
- "Energy balance in a warm world without the ocean conveyor belt and sea ice" (*Hu*). The project uses CCSM4 to assess the effects of an AMOC shutdown on energy fluxes under very warm future projections.
- "Impact of AMOC on Arctic sea ice and atmosphere heat transport into the Arctic" (Zhang). The project investigates how the AMOC affects Arctic sea ice variability in models and observations.
- "Submarine melting and freshwater export in Greenland's glacial fjords: The role of subglacial discharge, fjord topography and shelf properties" (*Cenedese, Straneo, and Heimbach*). The study aims to develop quantitative descriptions (parameterizations) to calculate basal melting of Greenland ice shelves and the associated freshwater input to the ocean.
- "Signature of the AMOC in the North Atlantic dynamic sea level" (*Yin, Griffies, and Zhang*). The project investigates linkages between observed AMOC variations and sea level along the east coast of North America.
- "The Panulirus hydrographic stations: Years 60-64" (*Bates and Johnson*). The project provides continuation of a six decade-long time series of physical and biogeochemical measurements at Hydrostation "S" and BATS in the subtropical North Atlantic.
- "Transport pathways in the North Atlantic: Searching for throughput" (*Rypina and Pratt*). The study investigates the degree to which ocean transport pathways influence physical, chemical, and biological tracers in the North Atlantic.

An overarching need to understand the mechanics and feedbacks by which climate system components are linked has prompted several studies to investigate how AMOC variability, imprinted on the upper ocean's heat content and/or the cryosphere, affects local and remote atmospheric patterns and phenomena.

Kelly and collaborators examine the relative contributions of atmospheric forcing and ocean dynamics to upper ocean heat content variability. Combining satellite altimetry, extensive SST records, and a canonical correlation analysis, they conclude that anomalous ocean circulation exerts greater influence than air-sea fluxes for the ocean heat budget in the Gulf Stream and the region north of 35°N. By focusing on the decadal frequencies – the latter related to the AMV – these ocean circulation impacts on upper ocean heat content are inferred to reflect AMOC variability. These findings are consistent with those of Buckley et al. (2014; 2015) discussed in section 2.3.1.

Vizy and Cook investigate the degree to which ocean-atmosphere interactions in the eastern equatorial and subtropical South Atlantic are influential in shaping regional and remote Atlantic climate variability (both in the ocean and atmosphere). Combining NASA observations, reanalysis products, and high resolution regional climate system models, they have identified a multidecadal (32-year) SST trend – warming along the equatorial African coasts and cooling over the subtropical South Atlantic – with associated atmospheric circulation shifts that weaken the coastal wind stress, decrease coastal upwelling, and increase coastal SST. Their work is motivated by the idea that Atlantic climate variability is sensitive to regions like this in which ocean-atmosphere interactions have generated low frequency SST trends, and that understanding both regional and remote climate impacts depends upon deciphering the details of small-scale ocean structures using latest generation coupled regional climate models.

In the Southern Hemisphere, meridional heat transport towards West Antarctica, where ice sheet melting is the largest, has been studied as an analog to similar melting and ocean overturning in the North Atlantic.

From Argo float trajectories, Zilberman et al. (2014) produce refined estimates of net meridional transports including evidence of regional modulations by the Southern Annular Mode (SAM) at 32°S, and by ENSO variability at latitudes both to the north and to the south. Gille (2014) provide further insights regarding shifting frontal features in the Antarctic Circumpolar Current (ACC), previously inferred to reflect poleward shifts in the winds over the Southern Ocean associated with intensification of the SAM. An index of mean latitude of water transported by the ACC, constructed from the altimeter record, show no such transport-latitude trend. This finding provides an alternative explanation to the sea surface height trends: that they may be indicative of steric expansion of the ocean rather than poleward shifts in geostrophic jets.

Extending their previous work on the synchronization of climate subsystems, *Tsonis and collaborators* show that AMOC related indices such as the AMV exhibit similar temporal structures to other decadally varying indices (e.g., PDO), indicating complex interactions of the AMOC with other remote climate phenomena. Based on simulations with the GFDL CM3 model, Kravtsov et al. (2014) suggest that the phase relation between the indices found in the model differs from that in the observations. These authors also suggest that CM3 underestimates multi-decadal variability in the North Atlantic, in contrast to recent results based on several different climate models (Laepple and Huybers 2014), but perhaps consistent with Lovejoy et al. (2013) who find that models underestimate multi-centennial variability. As part of this collaboration, *Duane and collaborators* explore relationships between regime shifts and synchronization by expanding the analysis to include more climate modes with a focus on establishing one or more mechanisms by which synchronization and coupling increases occur.

Hu et al. (2013a) find that the AMOC collapses in a scenario of strong future global warming, which leads to a large reduction in ocean heat transport. In his model simulations, Arctic warming is amplified by increased absorption of longwave radiation by greenhouse gases and by reduced sea ice cover. Other simulations of the next two centuries by Hu et al. (2013b) find that freshwater fluxes from melting ice sheets and glaciers only have an impact on the AMOC if they enter the North Atlantic, whereas fluxes from the West Antarctic Ice Sheet, provided they do not increase strongly from current rates, are not important for the AMOC.

Studying low frequency variability of summer Arctic sea ice extent (SIE) in the GFDL coupled climate model, *Zhang* finds that the AMOC, and its associated poleward heat transport, have played a significant role in its low frequency variability. The project suggests that an increasing AMOC trend (inflows of Atlantic water) may have contributed to the observed summer Arctic sea ice decline over the last 30 years and associated changes in atmospheric circulation. An intriguing corollary to this result is that an AMOC decline in the near future would slow, or possibly reverse, the observed SIE trend. The study further indicates that poleward heat transport by the atmosphere across the Arctic circle is compensated by AMOC-induced Atlantic ocean heat transport, in the sense that positive ocean heat transport anomalies to the Arctic leads to both reduced summer SIE and reduced poleward atmospheric heat transport. This suggests that recently observed changes in atmospheric circulation patterns and eddy heat transport may be a response to enhanced Atlantic Ocean heat transport rather than Arctic sea ice decline.

Combining existing observations, laboratory experiments, and high-resolution numerical simulations, *Cenedese and collaborators* seek to understand the dynamics that govern submarine melting of Greenland's glaciers and their associated fresh water fluxes. The dominant mechanics may include one or more factors: the magnitude and spatial distribution of subglacial discharge, hydrographic properties and stratification on the continental shelf, and fjord size and structure, particularly the height of a sill. The project aims to better understand the "wiring" of this component of climate system at a time when large and unanticipated changes are occurring at Greenland's margins, and to formulate parameterizations of melting and freshwater export, suitable for inclusion in large-scale ice sheet and climate models. This represents a key step for projecting sea level rise and the consequences of Greenland's fresh water input to the AMOC's sensitive regions.

Yin and colleagues study AMOC impacts on sea level rise along the east coast of North America. Focusing on a recently observed event, Goddard et al. (2015) find that a large (30%) AMOC reduction in 2009-2010 contributed to generating an extreme sea level rise (128 mm) for the following two years north of New York City. From regression analysis of tide gage observations and model simulations, they suggest a correlation between AMOC and sea level rise such that 1 Sv of AMOC weakening corresponds to 13-17 mm of coastal sea level rise along the northeast sector. The GFDL climate models (CM2.5 and CM2.6) support this relationship, further establishing that although anomalous along-shore wind stresses associated with the negative NAO in 2010 contributes to the extreme sea level rise, AMOC related steric anomalies dominate.

Physical and biogeochemical variability in the central subtropical North Atlantic has been monitored with biweekly hydrographic sampling at Hydrostation S since 1954 and monthly sampling at the Bermuda Atlantic Timeseries Study (BATS) sites since 1988. These sustained ocean observations have built a 60+ year record of physical properties (temperature, salinity, oxygen, nutrients) and 25+ years of biogeochemical (CO_2, alkalinity, organic carbon and nitrogen, fluorescence, phytoplankton pigments and bacteria counts) which have contributed to understanding upper ocean physics and climate connections, deep water processes, physical processes arising from measurements of gases and tracers, and biological processes and new production in this region.

Efforts are being made to clarify the transport pathways in the North Atlantic, with implications for physical, chemical, or biological tracers. In the context of two decades of declining American eel populations, Rypina et al. (2014) investigate connections between the North Atlantic circulation and the success rates of eel larvae using a coupled physical-biological model. At the end of their life cycle, American eel (Anguilla rostrata) migrate to the Sargasso Sea from freshwater habitats along the east coast of North America in order to spawn planktonic eggs. The eggs develop into larvae that then have to reach estuarine and freshwater nursery habitats along the North American coast within approximately their first year of life. While overfishing has contributed to the decline, oceanic variability on inter-annual scales also has a direct influence on the number of larvae that are reaching the coast each year from their spawning area in the subtropical gyre. A coupled biological–physical model is used to study how potential behavioral adaptations influence the ability of American eel larvae to reach near-coastal waters. The study implicates directional swimming as a behavior that result in distributions and transit times that most closely reflect observations, and the southwest region of the Sargasso Sea as the probable spawning area.

3 RESEARCH PRIORITIES

The near-term research priorities, articulated below, are based on the discussions that occurred during previous annual US AMOC Science Team meetings, but they are now reviewed and updated substantially following the discussions at the most recent annual meeting (September 2014) and subsequent TT teleconferences. Longer-term[1] priorities, also discussed at the September 2014 meeting, are provided as well, although they are still a work in progress. A discussion of progress towards accomplishing priorities and specific action items to be undertaken in 2015 are also included below.

3.1. Observing system implementation and evaluation

Observation of the AMOC is the cornerstone to improve our understanding of this complex flow system. Ideally, with no funding constraints, the goal here would be to observe full-depth, basin-wide, AMOC volume, heat, and fresh-water transports throughout the Atlantic Ocean basin at the highest possible temporal resolution (e.g., daily) from the southern limit at 34.5°S to the northern limits where Atlantic-Arctic exchanges occur. These observations would need to have sufficient spatial resolution to aid in understanding the observed AMOC variations (e.g., zonal resolution that would distinguish the details of boundary and interior flows). Finally, the needed assimilation and interpretation tools (reanalysis products, numerical models, etc.) would be developed to aid in the understanding and interpretation of the observations collected. This section describes progress towards these broad goals.

3.1.1 Near-term priorities

- Improving understanding of the meridional coherence (and/or lack thereof) of the AMOC and the mechanisms that control AMOC changes continues to be a high near-term priority. The newly deployed OSNAP array near 55°N, and the augmented elements of the SAMBA array at 34.5°S, will play key roles in this. Furthermore, development of dynamically consistent model-data synthesis methods to combine the heterogeneous observational pieces will also play an important role.
- Expansion of the existing observing system to better capture the deep ocean and to better quantify the role of deep temperature and salinity signals in contributing to AMOC variability continues to be a priority. Enhancements such as 'deep Argo', 'bio-Argo', full-depth gliders, and enhanced moored observations should be evaluated in the context of a full-depth observing system.
- Ensuring that AMOC estimates (and the key underlying measurements collected as part of the AMOC estimates) are made available in widely recognized locations such as the World Ocean Database, OceanSITES, the National Ocean Data Center, etc., is a *new near-term priority*. Improvement to

1. Long-term reflects program priorities and goals that will be achieved by additional resources and / or technological advancements over the next 5+ years. Developments in observational technologies that enable more observational coverage at reduced costs and in computational technologies that empower more extensive use of high-resolution models represent two examples of advancements. As such, the long-term priories do not reflect lower priority areas, but currently are limited by resources.

communications between different observing system groups is also a *recommended activity*, particularly between more established observing system groups and newer groups becoming involved at the national and international levels.

- Another *new near-term priority* is making sure that error estimates are produced and provided alongside AMOC estimates (and the constituent components). These error estimates should be made available on applicable time scales (days, weeks, months, and years) to provide the necessary precision information for analyses, inter-array comparisons, and for numerical model studies (where data are used for validation and/or for assimilation).

Improving understanding of the meridional coherence of AMOC, and the mechanisms that control AMOC changes continues to be one of the key areas of research. With the deployment of the new OSNAP array near 55°N in 2014, the continued success of the RAPID/MOCHA/WBTS array at 26.5°N, and the enhancements in 2012 to 2014 of the SAMBA array at 34.5°S, new latitudinal comparisons will be possible going forward – and in particular comparisons between the North and South Atlantic that are now possible with the new observations being made in the South Atlantic. Furthermore, crucial observations of key components of AMOC continue to be provided at other latitudes (e.g., Line W, SAM array, MOVE array, Norröna, Oleander and Davis Straits sections, the altimeter+Argo estimates at 41°N) and international observing systems (e.g., German array at 11°S).

Expansion of the existing observing system to better capture the deep ocean and to better quantify the role of deep temperature and salinity signals contributing to AMOC variability continues to be a priority. The existing global ocean observing system captures only the upper 2000 m of the ocean aside from a few specific locations (e.g., the RAPID/MOCHA/WBTS, OSNAP, SAMBA arrays), and as such does not measure the entire deep lower limb of the AMOC. New instruments and/or new applications of existing technologies, such as 'deep Argo', 'bio-Argo', full-depth gliders, and enhanced moored observations in the deep ocean, should be evaluated in order to aid in the future design of a more comprehensive (and cost-effective) deep ocean observing system.

AMOC estimates (and their key underlying component estimates) by their nature are complex and generally involve multiple groups and/or many different types of measurement systems. In order to gain the most benefits from these observations, it is crucial that the observational data are being made available to the widest possible spectrum of the science community. Making sure these observations are made available at widely recognized locations, such as the World Ocean Database, OceanSITES, the National Ocean Data Center, and other such locations can facilitate this. Furthermore, improvements to communications between different AMOC observing system groups, particularly between more established observing system groups and newer groups becoming involved at the national and international levels, can enable evaluation of the coherency of measured signals across the basin as well as lead to new collaborations.

Observations of any kind, including AMOC estimates and their constituent components, are really only valuable when combined with some sense of the accuracy of the observations. Research into AMOC has now progressed to the point where carefully derived error estimates need to be produced and provided alongside the observations themselves. Furthermore these error estimates need to be produced for the variety of time scales where AMOC data are analyzed, i.e., at time scales of days, weeks, months, and years. These error estimates are crucial for providing the needed precision information for the observations when they are used for inter-array comparisons, for example, and for numerical model studies (where observations are used for validation and/or for assimilation).

3.1.2 Long-term priorities

- Finding and/or developing new technologies and methods for studying the AMOC and its key components will be necessary moving forward in order to address the overall observing goals for AMOC in a world of finite resources.
- Development of plans to observe and study the shallow and deep pathways of the AMOC through the basin at locations away from the places of the few trans-basin arrays will be important in the long-term. This may involve future Lagrangian studies in the South Atlantic and/or tropical Atlantic regions similar to the ongoing work in the high-latitude North Atlantic, or it may involve the development of new technologies and/or techniques.
- Rigorous testing of data assimilation schemes is needed in order to better understand how the systems are using the data collected. Better communication is needed between the US AMOC community and the data assimilation community to test and potentially expand the set of collected observations that are assimilated into models.

Observations of the AMOC are expensive, at least on an ocean science scale, and developing newer and less-costly ways to make the observations needed is always a long-term goal. Advances in recent years on deeper-reaching Argo floats, and on autonomous data shuttling systems for deep ocean moored instruments, are being made, but the wide-scale implementation of these technologies is likely some years in the future. Nevertheless, this is a critical area for ongoing research as maintaining US AMOC observing programs for the needed multiple decades will require cost savings over the long term.

With the implementation of the long-planned array in the high-latitude North Atlantic (~55°N; OSNAP) and the significant (but not complete) implementation of the array in the subtropical South Atlantic (34.5°S; SAMBA), along with the continued successes of the mid-latitude North Atlantic array (26°N; RAPID/MOCHA/WBTS) and the observing systems measuring key components throughout the basin (e.g., Line W, SAM array, MOVE array, Norröna, Oleander and Davis Straits sections, the altimeter+Argo estimates at 41°N), some long-term focus needs to be put onto understanding the AMOC pathways between these locations. It is yet to be determined what methods might be used for these studies (e.g., Lagrangian floats, tracers, etc.), but it will be an important area of research in the future.

At present, only a subset of the data collected by the AMOC observing systems are assimilated into models – and the value of this is at times limited because the observational community and the assimilation community are not always well connected. It was noted at the September 2014 meeting, for example, that only a handful of the assimilation community members were present at the meeting. This is a challenge, particularly as there are many concerns about how the different assimilation systems use the data collected on AMOC. A specific suggestion was presented, possible only with better interaction with the assimilation community, that assimilation techniques could be tested through sampling an independent 'perfect' model and then assimilating those results into a family of unrelated models in order to test and improve our understanding of how a diverse set of assimilation systems would benefit from the incorporation of the AMOC data.

3.1.3 Action items

Several specific action items were agreed upon at the September 2014 US AMOC meeting in Seattle in order to address the aforementioned near-term and long-term goals – these action items are listed here in no particular order.

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

The information collected in the first two action items listed above will provide information for the Executive Committee to assess how well data is being made available to the widely recognized repositories (e.g., national and international data centers) and track progress in providing error estimates with AMOC estimates.

3.2. Evaluation of AMOC state, variability, and change

The charge of TT2 is to develop a holistic characterization of the present and historical circulation of the Atlantic Ocean and related ocean and atmospheric quantities. Essential to this task is the analysis of existing observations as well as the *joint interpretation of observational data and numerical model simulations*. Thus, this TT has natural synergies with TT1 (Observing system implementation and evaluation) and TT3 (AMOC Mechanisms and Predictability).

3.2.1 Near-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) in the North and South Atlantic. An emerging priority is to provide a more detailed characterization of AMOC flow pathways and their impact on variability.
- Continue development and investigation of AMOC "fingerprints." Modeling and observational studies that seek to refine our current understanding of the connection of AMOC to large-scale, historically well-observed properties of the climate system should be encouraged.
- Investigate connections between surface forcing (e.g., freshwater, heat, and momentum fluxes, NAO-related forcing) and historical AMOC variability.
- Develop a more comprehensive understanding of the strengths and weaknesses of existing global ocean reanalysis products and hindcasts using forward models as tools for investigating the circulation and transports in the Atlantic.

The community is combining different observational data streams with models to answer questions about both transport pathways and their variability. However, more efforts like these should be encouraged. These efforts could include attempts to refine our understanding of the AMOC and its associated transport of heat and freshwater. Using a combination of data sources (including the networks of XBTs, and Argo floats, satellite SST and SSH, current meters, moored and profiling CTD, passive tracers and the coordinated observational programs such as the RAPID/MOCHA, SAMBA/SAMOC, OSNAP, and DynAMITE) and eddy and non-eddy permitting numerical models, research should focus on the accurate and complete characterization of the circulation, the transports, and the underlying mechanisms that control the variability. As new data sets come on line, such as those from the South Atlantic, a continued emphasis on integrating the new data already available as well as model output should be encouraged. This could include examination of the pathways of abyssal flows, control of topography, and connections to the basin-wide circulation and associated variability.

This year we have moved the discussion of metrics from a research priority to an action item. The community should discuss metrics that can be used to characterize properties of the circulation that are *relevant to mechanistic and predictability studies* and that can be calculated both in observations and in models. Metrics should be proposed for inclusion in relevant coordinated model intercomparison projects.

Previous reports have prioritized studies related to the heat transport associated with the AMOC. In this report we add the study of freshwater transports. Both heat and freshwater transport are important for understanding geostrophic and buoyancy driven flows and for determining the global properties of the thermohaline circulation. In addition, important connections between the Arctic and Atlantic Ocean are manifested in both the salinity and temperature fields. Further development of our understanding of how mean and time-varying surface flux exchanges impact AMOC is a key near-term priority of TT3 as well (see section 3.3.1).

Uncovering the relationship between AMOC and the transport of oceanic tracers is also valuable for deepening our understanding of AMOC 'fingerprints.' Fingerprints are generally large-scale, historically well-observed properties of the climate and/or ecosystem that have characteristic signatures associated with AMOC fluctuations. The identification of fingerprints can be important for making inference about the historical behavior of AMOC prior to the existence of extensive subsurface observational networks. Earlier reports emphasized the development of links between AMOC and paleoclimate proxies as an avenue for considering millennial-scale AMOC variability. While these are still important sources of information, participation from that community has waned. We have made it one of our action items to reengage with the paleo-community.

One of the new priorities in last year's report (highlighted again this year) is the investigation of the connections between surface forcing (e.g., freshwater, heat and momentum fluxes, NAO-related forcing) and AMOC variability. Within TT2, the emphasis is on using existing observations to understand the role of atmospheric forcing in the observable past. This is naturally connected to the objectives of TT3; the idealized experiments carried out within that TT might provide important hypotheses to be tested with observations. In addition, there is a growing role for the use of coupled model simulations in investigation of these linkages.

Global ocean models that assimilate *in situ* hydrography and/or satellite observations are potentially powerful tools for estimating the state of AMOC and diagnosing the drivers of AMOC change. Unlike transports estimated from temporally and regionally confined observational networks, ocean synthesis products can provide transport information globally and at a variety of time-scales. Numerous ocean synthesis products, using a variety of assimilation methods and procedures, are available. However, it has been demonstrated that there is no consensus among these products on the evolution of the AMOC over the last 50 years. A near-term priority is to develop a more comprehensive understanding of the strengths and weaknesses of existing global ocean reanalysis products as well as historical hindcasts of forward models as tools for investigating the circulation and transports in the Atlantic.

3.2.2 Long-term priority

- Synthesize modeling and observational evidence to build scientific consensus on the variability and change of the AMOC over the last 50 years. Efforts within the data assimilation community should focus on reaching an accurate consensus (consistent with other lines of observational evidence) on the evolution of the AMOC over the last 50 years.

An ambitious long-term priority is to focus on reaching an *accurate consensus* among next-generation reanalysis products on the variability of the AMOC over the last 50 years and the mechanisms that contributed to the AMOC evolution. In support of this priority, one action item is to reach out to members of the ocean data assimilation community to encourage their participation in AMOC projects and science team meetings and to find out how the AMOC science teams can support the evaluation of global ocean reanalysis products.

3.2.3 Action items

- Based on progress in the last few years, members of TT2 should work towards defining a set of metrics that can be used to characterize properties of the circulation that are relevant to mechanistic studies and predictability. This will require coordination with TT1 and TT3 members. Metrics should be proposed for inclusion in relevant coordinated model inter-comparison projects.
- Reach out to members of the paleo-climate community to encourage their continued participation in AMOC projects and science team meetings.
- Reach out to members of the ocean data assimilation community to encourage their participation in AMOC projects and science team meetings.

3.3 AMOC mechanisms and predictability

Using multiple lines of corroborating evidence, TT3 seeks to identify the key physical processes at work in the maintenance and modulation of the AMOC in the past, present, and future in order to advance our ability to predict AMOC- related climate change. This overarching objective is based on the hypothesis that there are robust and potentially predictable driving mechanisms at work in nature on a variety of timescales, ranging from intra-seasonal to millennial, that can be anticipated from well-formulated theory, studied in isolation using appropriate idealized models, and identified as important in realistic 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 which 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 winds 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 ocean GCMs in this regard.
- Investigate the role of freshwater forcing, and south Atlantic freshwater transports, in determining the variability and stability of 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.

A key objective for TT3 continues to be to further develop our understanding of how mean and time-varying surface flux exchanges drive the mean and time-varying overturning circulation – this objective is common with TT2 as discussed in section 3.2.1. Internal variability of the atmosphere results in stochastic forcing of the ocean with the potential to excite low-frequency modes of the climate system. Coupled air-sea interactions are also likely to be important, with potential for oceanic control of surface fluxes on long timescales (and large spatial scales) as well as on short timescales (via mesoscale eddies and fronts). Surface transfers of buoyancy and momentum give rise to adjustment processes that can impact AMOC at locations far removed from the forcing, and more work is needed to understand the propagation mechanisms and the fidelity of our models in this regard. A specific priority is to address the lack of consensus in the literature regarding the importance of Southern Ocean winds – some idealized model studies (e.g., Wolfe and Cessi 2011; Nikurashin and Vallis 2012) indicate a strong sensitivity of AMOC to wind forcing in this region whereas more comprehensive GCM studies do not (e.g., Farneti and Delworth 2010; Gent and Danabasoglu 2011; Yeager and Danabasoglu 2014). The role of Southern Ocean winds relates to the question of how diabatic the AMOC circulation is. It could be that current GCMs retain, to some degree, the Veronis effect associated with spurious diabatic mixing which short circuits the AMOC, despite the use of state-of-the-art parameterizations designed to orient the horizontal mixing along isopycnals. Progress in understanding AMOC mechanisms, therefore, would seem to crucially depend upon developing a better sense of the magnitude and location of diabatic mixing in the ocean and whether GCMs represent that mixing correctly. Process studies using eddy-resolving models can and should be brought to bear to shed some light on these and other questions about the fidelity of mechanisms in current GCMs. Improved understanding and skillful modeling of AMOC variability can be expected to advance our skill in predicting AMOC and AMOC-related climate change, and it is important to demonstrate progress through participation in coordinated climate prediction efforts. An equally important priority for TT3 is to quantify the inherent predictability (i.e., sensitivity to initial condition uncertainty) properties of AMOC in both idealized and comprehensive models in order to develop a fundamental understanding of how AMOC-related ocean dynamics impart memory to the climate system.

3.3.2 Long-term priorities

TT3 long term priorities emphasize outstanding science questions, which will require more complex and resource-intensive models to fully explore, as well as the ongoing but incomplete synthesis efforts which attempt to build consensus knowledge about AMOC variability from the many disparate efforts/results coming out of the TT. These long-term priories include:

- 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 isotope-enabled coupled climate models.
- 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 work, including long coupled GCM simulations.
- Synthesize results from theoretical, idealized models, and complex GCM investigations into a common conceptual framework regarding key AMOC variability mechanisms and identify the resulting predictability of the AMOC.

Progress in understanding AMOC mechanisms on longer time scales than multidecadal remains an important long-term priority of TT3. Indeed while many studies have been focused on better understanding of AMOC fluctuations on decadal timescales, little is known about the drivers of the AMOC on centennial-to-millennial timescales or the representation of the AMOC on these long time scales in current GCMs relative to available paleo proxy data. The paleo community should be encouraged to engage in joint studies and data-sharing in order to promote understanding of AMOC variability on these long time scales.

Another long-term goal of TT3 is to translate the broader knowledge developed about AMOC variability and predictability mechanisms into reliable decadal climate forecasts. Recent work by Yeager et al. (2012), Robson et al. (2013), and Msadek et al. (2014) highlight the key role of the AMOC in the success of decadal climate forecasts for the particular case study of the mid-90's warming. More studies should be carried out to identify if and how the AMOC can be a source of skill for societally relevant climate impacts.

Most analysis of AMOC variability and predictability are so far based on relatively coarse oceanic models with a horizontal resolution of about 1° at most. Mesoscale processes have been shown to play a key role in accurately representing some important processes involved in AMOC fluctuations, like Nordic seas overflows (Zhang et al. 2011, Yeager and Danabasoglu 2012), interior pathways of NADW (Bower et al. 2009), the Agulhas leakage (Beal et al. 2011) or the Southern Ocean response to momentum and buoyancy fluxes (Farneti and Delworth 2010, Gent and Danabasoglu 2011). Hence, mesoscale eddy-resolving ocean models should be more fully incorporated into the toolkit used for AMOC mechanisms and prediction work, including long coupled GCM simulations.

The variability of the AMOC in GCMs has been shown to be strongly sensitive to small changes in parameters like horizontal viscosity or vertical mixing (Dananasoglu et al. in prep.), but there is still little understanding on the mechanisms through which the AMOC responds to variations in these physical parameters. Such issues are being addressed in theoretical studies (e.g., Nikurashin and Ferrari 2013), however, linking the results of idealized experiments to GCMs remains difficult. A new priority of TT3 will seek a better coordination between theoretical, idealized models, and complex GCM investigations with the goal of developing a common conceptual framework regarding key AMOC variability mechanisms and identifying the resulting predictability of the AMOC.

3.3.3 Action items

The specific actions to be encouraged over the next year include:

- Engage the paleo community to develop joint studies and undertake data-sharing in order to promote understanding of AMOC variability on the long timescales (centennial to millennial), which heretofore have not received as much focus as decadal, due in part to resource constraints.
- Evaluate the feasibility of coordinating an eddy-resolving version of the Ocean Model Intercomparison Project (OMIP) component of CMIP6, as a step towards addressing the robustness of AMOC variability mechanisms to ocean model resolution.
- In order to make the best use of eddy-resolving models towards TT3 near-term objectives, schedule a discussion session at the 2015 Bristol meeting aimed at identifying some concrete, feasible, and high-priority process modeling studies related to AMOC variability mechanisms.
- Closely monitor the AMOC-related results coming out of the current Climate Process Team on ocean internal mixing and look into coordinated studies focused on the sensitivity of AMOC to background diapycnal mixing.

3.4 Climate sensitivity to AMOC: Climate-ecosystem impacts

The potential for the evolving AMOC to affect other components of the Earth system – its hydrologic cycle, cryosphere, sea level, marine ecosystems, and carbon budgets – in societally relevant ways, strongly motivated and shaped the objectives of the nascent US AMOC program. The resultant expansion of the mechanistic and dynamical framework describing the AMOC and its variability has seen parallel progress in identifying how that variability influences other physical and biogeochemical systems – both locally and remotely. At the 2014 annual meeting, a special session highlighted research pertaining to AMOC linkages to climate variability, with oral presentations drawing attention to impacts on Arctic sea ice, the Northern Hemisphere Inter-Tropical Convergence Zone, and AMOC interactions with tropical Atlantic variability. Presentations relating to the topics of marine ecosystem and carbon cycle impacts were notably lacking, and it is incumbent for the Science Team to initiate and nurture synergies with these communities. The external review report issued in 2013 recommended developing broader interactions through focus groups organized around AGU meetings (Talley et al. 2013).

During the breakout session at the meeting and subsequent teleconferences, TT4 revisited its research priorities and constructed a four-themed framework within which specific topics were articulated.

3.4.1 Near-term priorities

- Identify the mechanisms by which AMOC variability, imprinted on SST and/or the cryosphere, affects local and remote atmospheric patterns and phenomena.
- Assess AMOC impacts on the cryosphere, particularly Arctic sea ice and the Greenland ice sheet.
- Assess AMOC impacts on global and regional sea level.
- Improve understanding of how AMOC variability affects ocean-atmosphere exchanges of carbon, biogeochemical cycles, and marine ecosystems.

Advances to understanding how the atmosphere responds to AMOC-generated SST changes, highlighted in previous US AMOC annual reports, have established that AMOC variability exerts important influences on the North Atlantic climate, including the climate of neighboring continental regions. These have come about in the general context of atmospheric baroclinicity and its controls on remote hydroclimate characteristics (e.g., tropical and extratropical storm activity, droughts and flood events). The topics of highest priority identified by TT4 members include understanding: i) changes in the rate of warming (e.g., the recently observed "hiatus" in the trend of rising upper ocean heat content); ii) AMOC impacts on tropical cyclone activity (via upper ocean heat content and vertical shear); and iii) impacts on position of the ITCZ and tropical precipitation patterns.

An emerging hypothesis regarding synchronization of hemispheric climate subsystems calls for a more careful examination of the AMOC's global effects. Wyatt et al. (2012) provides evidence for propagation of AMV signals throughout the Northern Hemisphere via a sequence of atmospheric and lagged oceanic teleconnections, which the authors term the "stadium wave." Science Team members are actively pursuing several lines of inquiry to explore these ideas and their implications.

AMOC variability is expected to influence the Greenland ice sheet – directly through changes in ocean heat transport (which can directly affect rates of submarine melt of marine terminating glaciers) and indirectly through changes in atmospheric forcing and storm tracks. Freshwater discharge associated with land-ice loss (including surface melt, submarine melt, and icebergs) is very likely, in turn, to affect the AMOC, particularly in the regions of deep mixing where the upper limb feeds the lower limb. In other words, the ocean – ice sheet interactions are very much a two-way system. Current state of knowledge and research priorities are summarized in a number of documents (Straneo et al. 2013; Heimbach et al. 2014) produced by the US CLIVAR Working Group on Ice Sheet-Ocean Interactions (GRISO – see http://www.usclivar.org/working-groups/greenland-ice-sheet-ocean-interactions – many of the research priorities discussed in these references pertain to the US AMOC program objectives). GRISO has now transformed into an international science network (http://web.whoi.edu/griso/) and is currently forming new working groups to address some of the priorities identified, including obtaining high-accuracy bottom topography of key outlet glaciers, fjords, continental shelves and establishing a Greenland Ice Ocean Observing system. Continued interaction with the GRISO community and its new science network will be important for future collaborative investigations to understand the role of AMOC variability in the mass changes of the Greenland ice sheet.

AMOC variability also exerts an influence on Arctic sea ice through modulation of ocean heat transport into the Arctic. In the Barents Sea, seasonal sea ice extent has exhibited declining trends that are significantly anti-correlated with Atlantic inflows from 1979 to 2013. Atmospheric circulation and heat transport across the Arctic Circle may have intriguing relationships with AMOC variability, as R. Zhang's work with the GFDL coupled climate model suggests. Utilizing both model simulations and observations, additional studies that explore linkages between Arctic sea ice and AMOC variability are clearly needed. The specific questions regarding Arctic sea ice as it relates to AMOC identified as high priority topics include: i) How will changes in the AMOC influence Arctic sea ice regionally and as a whole? ii) What mechanisms are seasonally important (e.g., winter vs. summer)? and iii) What is the fate of heat transport through Fram Strait and in the Barents Sea and what are the processes that control this in models?

The AMOC influences global sea level rise in two principal ways: i) steric changes – by modulating the partitioning of ocean heat between the upper and deeper layers, and ii) increased mass input – melting of the Greenland ice sheet by subsurface ocean warming. The AMOC also has an impact on regional sea levels in the North Atlantic, a linkage that has been established along the East Coast of the US with both observations and model results. On inter-annual timescales, it appears to be a leading factor that explains the temporal and spatial characteristics of the coastal sea level rise along the US east coast, particularly its northeastern sector

(Goddard et al. 2015). Furthermore, ocean dynamics related to the AMOC can result in multidecadal variability and long-term trends of sea level along the US East Coast, and is responsible for sea level rise acceleration from Cape Hatteras to Cape Cod. Regional sea level rise projections and coastal planning now take the AMOC into account. Long-term sea level data from high-quality tide gauges stations along the North American east coast should be exploited to further establish linkages between past sea level variability and changes of the AMOC. The research questions of high priority as they pertain to AMOC include: i) Why is regional sea level rise along the US East Coast greater than the global average? and ii) What are the dominant processes controlling spatial and temporal variability in the rates of regional sea level rise?

Ocean physics and biology plays a pivotal role in the global carbon cycle via several key processes. The solubility pump, driven by uptake of carbon dioxide (CO_2) at the ocean surface and subduction of inorganic carbon-rich water at high latitudes, and the biological carbon pump, driven by the production, sinking, and subsequent remineralisation of organic material back to CO_2, together transport in excess of 100 Pg C yr^{-1} into the oceans interior (Volk and Hoffort, 1985). The global ocean has absorbed approximately 25% of the CO_2 emitted to the atmosphere by anthropogenic processes, principally fossil fuel combustion (Khatiwala et al. 2013) much of it in the North Atlantic Ocean. There are complex feedbacks between the solubility and biological carbon pumps and uptake and storage of anthropogenic carbon in the global ocean (e.g., Tanhua et al., 2013) and understanding contemporary oceanic carbon uptake, storage and transport is key to predicting the future evolution of atmospheric CO_2 levels, climate impacts, and the gradual acidification of the global ocean (e.g., Bates et al. 2014). The AMOC is a key driver of biogeochemical dynamics, and for the strength and variability of the North Atlantic Ocean biological carbon pump and air-sea CO_2 fluxes. Important mechanisms influencing the transport and storage of anthropogenic CO_2 in the basin thus relate to the balance and variability of northward and southward transport of heat and carbon, and strength and variability of the biological carbon pump in the subpolar and subtropical gyres. Related specific questions include: i) How can the paleo record be utilized to better understand the impact of AMOC on ocean carbon uptake and the terrestrial carbon cycle? ii) What processes are controlling carbon draw down into the deep ocean and variability in that system? iii) What physical parameters (i.e., upper ocean stratification, mixed layer depth, nutrient input) are needed by the ocean carbon/biogeochemistry community to improve understanding of these? and iv) Does satellite productivity correlate with AMOC variability?

3.4.2 Long-term priorities

The long-term goal of TT4 is to understand how AMOC variability affects other components of the Earth system – its climate, hydrologic cycle, atmospheric circulation, coupled phenomena (e.g., ENSO, monsoons), cryosphere, sea level, marine and terrestrial ecosystems, biogeochemical cycles, and carbon budgets – both locally and remotely.

3.4.4 Action items

- Connect with the existing US CLIVAR working groups (i.e., Extremes WG, Eastern Tropical Ocean Synthesis WG) to assess the degree to which AMOC variability is causally linked to observed and projected shifts in these climate phenomena.
- Promote studies within the Arctic observational and modeling communities investigating how AMOC variability will affect Arctic sea ice in the near future.
- Coordinate with the Coastal Ocean Observing community (e.g., MARACOOS) to assess the linkages between AMOC and the changes observed on the shelves.

- Connect with the Ocean Carbon Biogeochemistry program to proactively assess the high priorities of the carbon and biogeochemical research communities. Where can the AMOC community contribute with respect to better understanding carbon uptake, changes in temperature, upwelling, and other physical processes influencing ecosystems dynamics and geographic distributions?
- Attend the Southern Ocean and Ocean Carbon Uptake joint workshop in December 2014 at AGU Fall Meeting.

4 RELATED ACTIVITIES TO SUSTAIN

This section is complementary to the US AMOC program research priorities discussed above. It is very similar in content to the previous annual reports, detailing activities to achieve both near-term priorities and long-term goals.

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, etc.) 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 for brevity. 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 time scales, including the AMOC observing projects. These programs are based on the detailed requirements for the sustained ocean observing system that were established at the OceanObs'09 Conference (http://oceanobs09.net). The responsibility for the design and implementation of these observing systems lies with NASA, NOAA, and 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 maintaining the observing systems, while at the same time working to enhance and improve our international relationships in order to best utilize the capabilities of the many nations of the world.

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 time scales. An assessment of whether this relationship exists on interdecadal time scales continues to be of central importance to the US AMOC program goals. Unfortunately, participation from the paleo community in the US AMOC program has waned in recent years. It is, thus, crucial for the US AMOC Science Team to reach out to members of the paleo-climate community to encourage their continued participation in various AMOC projects and Science Team meetings.

Regarding fingerprints of AMOC variability on multi-decadal and centennial scales, following activities should be considered:

- 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 multi-decadal 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 all the previous US AMOC annual reports, starting with the very first report published in October 2008. 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 annual reports:

- Support for designing and performing coordinated experiments to investigate robustness of proposed AMOC variability mechanisms and to test the AMOC response to specific forcings (e.g., NAO, AMV, Southern Ocean winds).
- 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, particularly at universities.
- 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 the infrastructure to analyze 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 time scales. 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 2014 agency support

NASA, NOAA, NSF, and DOE, the federal agency sponsors of the US AMOC Science Program in FY 2014, funded a total of 63 projects supporting the work of approximately 100 US scientists (Appendix B). Of these projects, 12 were newly awarded in 2014. NASA provided $800K to support 8 projects exploiting satellite observations and datasets, and characterizing the attributes, variability, and mechanisms of the AMOC, with new projects on South Atlantic and equatorial variability. NOAA allocated over $5.7M to a total of 19 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, with a new project on the South Atlantic MOC. NSF provided between $7M to $8M in incremental funding to 27 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. NSF new and continuation awards in 2014 included examination of upstream sources of Denmark Strait Overflow, Atlantic water boundary current in the eastern Arctic, melting and freshwater input from the Greenland ice sheet, examination of wave processes across 26°N, and continuation of the Line W at 39°N to extend 10-year time series of the deep western boundary current and Gulf Stream. DOE allocated $1.9M for 9 modeling studies examining the mechanisms of AMOC variability and predictability as well as the influence of AMOC on climate and sea level variability and change, with new projects investigating global climate under different background conditions, including the absence of AMOC and sea ice.

The four agencies, through their support of the US CLIVAR Project Office budget, cosponsored the 2014 US AMOC Science Team Meeting held in Seattle, WA, September 9-11, 2014. The meeting assembled over 80 participants, including Science Team members, other interested US and international scientists, and program managers to survey individual project research findings, define near- and long-term science priorities, and identify specific actions and collaborative activities to accelerate scientific understanding.

5.2 FY 2015 outlook

With the completion of 15 projects during 2014, there are 48 ongoing US AMOC projects supported by NASA, NOAA, NSF, and DOE at the start of FY 2015. NASA will solicit new projects in its ROSES2015 Research Announcement for analysis and interpretation of the ocean circulation using satellite and *in situ* data. NOAA is not soliciting new projects for 2015. NSF will accept new AMOC project proposals through its standard solicitations for the Physical Oceanography and the Climate and Large-scale Dynamics programs. DOE will award new projects in 2015 from the pool of project proposals submitted in 2014.

The agencies are providing support to US CLIVAR Project Office to co-sponsor the UK RAPID / US AMOC 2015 International Science Meeting scheduled for July 21-24, 2015 in Bristol, UK.

6 SUMMARY

The US AMOC program, now in its seventh year, has been developed as a US interagency program to increase understanding of AMOC. The purpose of the program is to bring together researchers studying AMOC and build collaborations among modeling and observational communities to address problems related to AMOC state, variability, predictability, and climate impacts. The program currently includes over 50 funded projects. Annual program meetings, held either independently or jointly with the UK RAPID program, have been very successful in bringing together program scientists to share research results, develop collaborative projects, and identify near- and long-term research priorities and goals.

Research highlights and accomplishments of the program during 2014 are reviewed within the body of this document. Updates to the near- and long-term priorities and goals that emerged from the discussions during the 2014 Annual Science Team Meeting and during the subsequent TT teleconferences are also included along with TT specific action items. The knowledge of AMOC variability and its linkages to climate variability is steadily advancing, but a thorough understanding of AMOC variability and its mechanisms still remains elusive. The summary below highlights a few of the accomplishments of the program in 2014:

1. The observational system for monitoring the AMOC was greatly enhanced in the past year with the deployment of a high-latitude North Atlantic observing array (OSNAP: Overturning in the Subpolar North Atlantic Program). This array fulfills an important priority that was identified in the original US AMOC implementation plan – that of measuring the AMOC near the formation regions of the lower limb of the main Atlantic overturning cell. The OSNAP array consists of two legs observing the mouths of the Labrador and Norwegian-Greenland Seas. The array has an initial planned lifetime of four years. Additional key observations in this region are being collected in Davis Strait, Denmark Strait, and across the inflows to the Nordic Seas.
2. The AMOC array at 26.5°N, comprised of the MOCHA and Western Boundary Time Series (WBTS) projects together with the UK RAPID-MOC project, has now collected a decade of fully trans-basin, full-water-column, daily estimates of the volume and heat transports. This data continues to form the backbone of the AMOC observing system, and it is routinely used for testing numerical models used in AMOC studies. Other key observations being collected in the subtropical North Atlantic include the lower AMOC branch observations made by the MOVE project, the repeated Gulf Stream sections collected by the Oleander project, and the decade of Deep Western Boundary Current (DWBC) and Gulf Stream measurements collected on Line W.
3. The South Atlantic MOC observing system at 34.5°S, anchored by the SAM project, continues to develop, with major new enhancements to the trans-basin array deployed in 2014 by partners in South Africa and with important contributions continuing from France, Brazil, and Argentina. Several new studies are looking at ways of further enhancing the South Atlantic MOC observing system using satellite gravimetry and/or a combination of satellite and *in situ* data as well as synthesis products and models.
4. The pathways of the lower limb of AMOC have been described in greater detail, including the pathway of North Atlantic Deep Water in the subpolar gyre and through the Charlie-Gibbs Fraction Zone. In addition,

the flow of the DWBC as it travels from the Southwestern Atlantic through to exiting the Atlantic south of Africa has been described in greater detail using both observations and models.

5. An increased use of satellite products along with Argo data have allowed more detailed examination of the linkages between heat content, heat transport, and AMOC. Comparisons against ocean reanalysis/state estimate products have facilitated more detailed analysis of the connections between AMOC and the pattern of subsurface warming in the Atlantic Ocean. In addition, AMOC at 26.5°N has been shown to provide an independent metric for evaluation of state estimates.
6. Current reanalysis products show differing AMOC trends over the 20th century. This uncertainty results mainly from the different methodologies used in assimilating the data that constrain the AMOC and from the lack of robustness of AMOC mechanisms in the models used to derive the reanalysis. Some mechanisms including buoyancy forcing over the Labrador Sea or deep flow interaction with bottom topography appear to be key in controlling the simulated AMOC fluctuations, but their robustness across models remains to be shown. This disparity among the reanalysis products regarding their AMOC trends is not found in forced ocean simulations, which show consistent AMOC variability and trend among each other.
7. An emerging hypothesis regarding synchronization of hemispheric climate subsystems calls for further consideration of mechanisms by which Atlantic multidecadal variability signals propagate throughout the Northern Hemisphere. Evidence for a sequence of atmospheric and lagged oceanic teleconnections, labeled the "stadium wave," has spurred several lines of inquiry to develop mechanistic and empirical-dynamical models of this phenomenon, and to determine why it is absent in current generation of general circulation models.
8. AMOC variability exerts an influence on Arctic-sea ice through modulation of ocean heat transport into the Arctic. In the Barents Sea, seasonal sea ice extent has exhibited declining trends that are significantly anti-correlated with Atlantic inflows from 1979 to 2013. Atmospheric circulation and heat transport across the Arctic Circle may have intriguing relationships with AMOC variability, as work with a coupled climate model suggests.

There are several new near-term research priories that emerged from recent discussions. These include: ensuring that AMOC estimates (and the key underlying measurements collected as part of the AMOC estimates) are made available in widely recognized locations; improvement to communications between different observing system groups, particularly between more established observing system groups and newer groups becoming involved at the national and international levels; making sure that error estimates are produced and provided alongside AMOC estimates (and the constituent components); providing a more detailed characterization of AMOC flow pathways and their impacts on variability; developing a more comprehensive understanding of the strengths and weaknesses of existing global ocean reanalysis products and hindcasts; quantifying the magnitude, location, and physical mechanisms associated with interior diapycnal mixing in the ocean and evaluating the realism of current ocean GCMs in this regard; investigating the role of freshwater forcing, and south Atlantic freshwater transports, in determining the variability and stability of AMOC; expanding the use of eddy-resolving models in AMOC-related studies; and identifying the mechanisms by which AMOC variability, imprinted on SST and/or the cryosphere, affects local and remote atmospheric patterns and phenomena.

For the first time, the annual report contains several long-term priorities for each TT, following the recommendations of the External Review Committee of the US AMOC program (Talley et al. 2013). A summary of these is given below:

Task Team 1

Find and/or develop new technologies and methods for studying the AMOC and its key components to address the overall observing goals for AMOC in a world of finite resources.

Develop plans to observe and study the shallow and deep pathways of the AMOC through the basin at locations away from the places of the few trans-basin arrays.

Test data assimilation schemes to better understand how the systems are using the data collected, and improve communication between the US AMOC community and the data assimilation community.

Task Team 2

Synthesize modeling and observational evidence, including data assimilation, to build scientific consensus on the variability and change of the AMOC over the last 50 years.

Task Team 3

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.

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 work, including long coupled GCM simulations.

Synthesize results from theoretical, idealized models, and 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 affects other components of the Earth system – its climate, hydrologic cycle, atmospheric circulation, coupled phenomena (e.g., ENSO, monsoons), cryosphere, sea level, marine and terrestrial ecosystems, biogeochemical cycles, and carbon budgets – both locally and remotely.

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

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Appendix A: Terms of Reference for the US AMOC Task Teams

Task Team 1: AMOC Observing System Implementation and Evaluation

Members	*Institution*
Molly Baringer	NOAA Atlantic Oceanographic and Meteorological Laboratory
Kathleen Donohue	University of Rhode Island
Charles Eriksen	University of Washington
Marieke Femke de Jong	Woods Hole Oceanographic Institution
Gustavo Goni	NOAA Atlantic Oceanographic and Meteorological Laboratory
George Halliwell	NOAA Atlantic Oceanographic and Meteorological Laboratory
Patrick Heimbach	Massachusetts Institute of Technology
Bill Johns	University of Miami
Felix Landerer	Caltech/NASA Jet Propulsion Laboratory
Craig Lee	University of Washington
Susan Lozier	Duke University
Chris Meinen (Chair)	NOAA Atlantic Oceanographic and Meteorological Laboratory
Renellys Perez (Vice-chair)	Univeristy of Miami/NOAA Atlantic Oceanographic and Meteorological Laboratory
Thomas Rossby	University of Rhode Island
Uwe Send	Scripps Institution of Oceanography
John Toole	Woods Hole Oceanographic 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, JASON, the Global Drifter Array, and collection of satellites returning ocean surface and meteorological information. Near-tem 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 changes. Augmented elements of an Atlantic-wide monitoring system (OSNAP to be implemented and enhancements to SAM to be proposed), as well as dynamically consistent model-data synthesis methods to combine the heterogeneous observational pieces (including satellite data), will play an important role.
- Expand the existing observing system to better capture the deep ocean and quantify the role of deep temperature and salinity signals in controlling AMOC variability continues to be a priority. Enhancements such as 'deep Argo', full-depth gliders, and enhanced moored observations should be evaluated in the context of a full-depth observing system.

Task Team 2: AMOC State, Variability, and Change

Members	*Institution*
Molly Baringer	NOAA Atlantic Oceanographic and Meteorological Laboratory
Amy Bower	Woods Hole Oceanographic Institution
James Carton	University of Maryland
Ruth Curry	Woods Hole Oceanographic Institution
Gustavo Goni	NOAA Atlantic Oceanographic and Meteorological Laboratory
Sirpa Häkkinen	NASA Goddard Space Flight Center
Alicia Karspeck (Vice-chair)	National Center for Atmospheric Research
Kathryn Kelly	University of Washington
Matthias Lankhorst	Scripps Institution of Oceanography
Jonathon Lilly	University of Rhode Island
Susan Lozier	Duke University
Sudip Majumder	NOAA Atlantic Oceanographic and Meteorological Laboratory
Julian McCreary	University of Hawaii
Mike McPhaden	NOAA Pacific Marine Environmental Laboratory
Renellys Perez	NOAA Atlantic Oceanographic and Meteorological Laboratory
Peter Rhines	University of Washington
Irina Rypina	Woods Hole Oceanographic Institution
C. K. Shum	Ohio State University
Michael Spall	Woods Hole Oceanographic Institution
Fiamma Straneo	Woods Hole Oceanographic Institution
Zoltan Szuts	University of Washington
Luanne Thompson (Chair)	University of Washington
Josh Willis	Caltech/NASA Jet Propulsion Laboratory
Xiao-Hai Yan	University of Delaware
Rong Zhang	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. Near-term priorities for this task team include:

- Understand the relationships between surface heat and freshwater fluxes and AMOC metrics and establish connections to climate signals such as the NAO.
- Use observations, data assimilation and coupled high and low-resolution models, characterize the variability of the AMOC over the past few decades throughout the Atlantic basin, and place uncertainty bounds on these estimates.
- Investigate MHT attributed to AMOC in forward, assimilation, non-eddy-resolving, eddy-resolving models and compare with observational data when possible. Evaluate the differences among models and biases against observational estimates.
- Understand the interaction of AMOC with variability in North Atlantic subpolar region and coordinate analyses with OSNAP efforts. Describe and understand mechanisms of any signatures of meridional coherence of AMOC (especially between subpolar and subtropical regions) from both model and observational analyses.

Task Team 3: AMOC Mechanisms and Predictability

Members	*Institution*
Grant Branstator	National Center for Atmospheric Research
Paola Cessi	Scripps Institution of Oceanography
Ping Chang	Texas A&M University
Wei Cheng	University of Washington
Alan Condron	University of Massachusetts
Gokhan Danabasoglu	National Center for Atmospheric Research
Tom Delworth	NOAA Geophysical Fluid Dynamics Laboratory
Shenfu Dong	University of Miami
Gregory Duane	University of Colorado
Alexey Fedorov	Yale University
Benjamin Harden	Woods Hole Oceanographic Institution
Chris Hill	Massachusetts Institute of Technology
Aixue Hu	National Center for Atmospheric Research
Julian McCreary	University of Hawaii
Rym Msadek (Chair)	NOAA Geophysical Fluid Dynamics Laboratory
Cécile Penland	NOAA Earth System Research Laboratory
Robert Pickart	Woods Hole Oceanographic Institution
Rui Ponte	Atmospheric and Environmental Research
Tony Rosati	NOAA Geophysical Fluid Dynamics Laboratory
Andreas Schmittner	Oregon State University
Michael Spall	Woods Hole Oceanographic Institution
Eli Tziperman	Harvard University
Chunzai Wang	NOAA Atlantic Oceanographic and Meteorological Laboratory
Wilbert Weijer	Los Alamos National Laboratory
Jiayan Yang	Woods Hole Oceanographic Institution
Steve Yeager (Vice-chair)	National Center for Atmospheric Research
Rong Zhang	NOAA Geophysical Fluid Dynamics Laboratory

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. In the near-term, the task team will endeavor to:

- Clarify the relative roles of heat/freshwater/momentum forcing, Nordic Seas overflows, Southern Ocean and Arctic Ocean teleconnections, coupled air-sea feedbacks, and mesoscale processes on AMOC variability and stability.
- Develop a synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational data.

The task team will also coordinate with the US CLIVAR Decadal Predictability Working Group as well as the CLIVAR Working Group on Ocean Model Development and CLIVAR Global Synthesis and Observational Panel.

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

Members	*Institution*
Nick Bates	Bermuda Institute of Ocean Sciences
Martha Buckley	George Mason University
Claudia Cenedese	Woods Hole Oceanographic Institution
Ping Chang	Texas A&M University
Ruth Curry (Chair)	Woods Hole Oceanographic Institution
Sarah Gille	Scripps Institution of Oceanography
Terry Joyce	Woods Hole Oceanographic Institution
Kathryn Kelly	University of Washington
Sergey Kravtsov	University of Wisconsin-Milwaukee
Zhengyu Liu	University of Wisconsin
Irina Rypina	Woods Hole Oceanographic Institution
R. Saravanan	Texas A&M University
Andreas Schmittner (Vice-chair)	Oregon State University
Fiamma Straneo	Woods Hole Oceanographic Institution
Anastasios Tsonis	University of Wisconsin
Jianjun Yin	University of Arizona
Dongxiao Zhang	NOAA Pacific Marine Environmental Laboratory

The task team is charged with better understanding the links between the AMOC and North Atlantic SST and teleconnections with climate variability elsewhere. Activities include:

- Further define the sensitivity and response of climate to AMOC variability.
- Assess AMOC impacts on the cryosphere, particularly Arctic sea ice and the Greenland Ice Sheet.
- Assess AMOC impacts on global and regional sea level change.
- Improve understanding of how AMOC variability affects ocean-atmosphere exchanges of carbon, biogeochemical cycles, and associated changes in marine ecosystems.

Appendix B: AMOC Projects Active in 2014

PIs	Project	Sponsor	Duration	Page
Molly Baringer (NOAA/AOML) Sylvia Garzoli (U. Miami; NOAA/AOML) Gustavo Goni (NOAA/AOML) Shenfu Dong (U. Miami; NOAA/AOML)	State of the Climate: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean	NOAA	Jun 2005 – Ongoing	51
Molly Baringer (NOAA/AOML) Christopher Meinen (NOAA/AOML) Sylvia Garzoli (U. Miami; NOAA/AOML)	Western Boundary Current Time Series (WBTS)	NOAA	Jun 2005 – Ongoing	53
Nicholas Bates (BIOS) Rodney Johnson (BIOS)	The Panulirus Hydrographic Stations: Years 59-64	NSF	Apr 2012 – Mar 2017	55
Amy Bower (WHOI) Michael Spall (WHOI)	A Crossroads of the AMOC: The Charlie-Gibbs Fracture Zone	NSF	Oct 2009 – Sep 2015	58
Grant Branstator (NCAR) Haiyan Teng (NCAR) Gerald Meehl (NCAR)	Initial Value Predictability of Intrinsic Oceanic Modes and Implications for Decadal Prediction over North America	DOE	Sep 2010 – Sep 2014	60
Martha Buckley (George Mason U.) Rui Ponte (AER) Jason Furtado (AER) Patrick Heimbach (MIT)	Identifying Mechanisms of AMOC Variability in ECCO State Estimates and CMIP5 Models	NOAA	Sep 2013 – Aug 2016	61
James Carton (U. Maryland) Gennady Chepurin (U. Maryland) Sirpa Häkkinen (NASA/GSFC) Michael Steele (U. Washington)	Using Ocean Data Assimilation to Explore Arctic/Subarctic Climate Variability	NSF	Sep 2012 – Aug 2015	63
Claudia Cenedese (WHOI) Fiamma Straneo (WHOI) Patrick Heimbach (MIT)	Submarine Melting and Freshwater Export in Greenland's Glacial Fjords: The Role of Subjlacial Discharge, Fjord Topography, and Shelf Properties	NSF	Nov 2014 – Oct 2017	65
Paola Cessi (UCSD/SIO) Christopher Wolfe (Stony Brook U.)	Pulling the Meridional Overturning Circulation from the South	DOE	Sep 2010 – Aug 2015	66
Ping Chang (Texas A&M) Link Ji (Texas A&M) Ben Kirtman (U. Miami)	Role of Internal Atmospheric Variability in the AMOC	NOAA	Sep 2011 – Sep 2014	68
Ping Chang (Texas A&M) Gokhan Danabasoglu (NCAR) Steve Yeager (NCAR)	Understanding Changes in the AMOC during the 20th Century Using IPCC AR5 Model Ensembles	NOAA	Sep 2013 – Aug 2016	69
Alan Condron (U. Massachusetts) Raymond Bradley (U. Massachusetts)	High-Resolution Model Development to Quantify the Impact of Icebergs on the Stability of the AMOC	DOE	Sep 2011 – Sep 2014	72
Ruth Curry (WHOI) Kurt Polzin (WHOI)	Dynamics of Abyssal Mixing and Interior Transport Experiment (DynAMITE)	NSF	Nov 2009 – Oct 2014	74

PIs	Project	Sponsor	Duration	Page
Gokhan Danabasoglu (NCAR) Steve Yeager (NCAR) Alicia Karspeck (NCAR) Joe Tribbia (NCAR) Tom Delworth (NOAA/GFDL) Rym Msadek (NOAA/GFDL) Tony Rosati (NOAA/GFDL) Young-Oh Kwon (WHOI) Claude Frankignoul (WHOI)	A Collaborative Multi-Model Study: Understanding AMOC Variability and their Impacts on Decadal Prediction	NOAA	Sep 2013 – Aug 2016	75
Gokhan Danabasoglu (NCAR) Jeffrey Andreson (NCAR) Grant Branstator (NCAR) Keith Lindsay (NCAR) Joe Tribbia (NCAR) Claude Frankignoul (WHOI) Young-Oh Kwon (WHOI) Minghua Zhang (Stony Brook U.)	Mechanisms, Predictability, Prediction, and Regional and Societal Impact of Decadal Climate Variability	NSF	Mar 2013 – Feb 2018	80
Marieke Femke de Jong (WHOI) Amy Bower (WHOI)	Pathways to the Denmark Strait Overflow: A Lagrangian Study in the Iceland Sea	NSF	Sep 2013 – Mar 2018	85
Kathleen Donohue (U. Rhode Island) Charles Flagg (Stony Brook U.) Thomas Rossby (U. Rhode Island)	The Oleander Project: Sustained Observations of Ocean Currents in the NW Atlantic between New York and Bermuda	NSF	Sep 2008 – Aug 2015	86
Alexey Fedorov (Yale U.)	A Generalized Stability Analysis of the AMOC in Earth System Models: Implication for Decadal Variability and Abrupt Climate Change	DOE	Sep 2011 – Sep 2014	89
Sarah Gille (UCSD/SIO) Doug Martinson (Columbia U./LDEO)	Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt	NOAA	Aug 2010 – Jul 2014	91
Gustavo Goni (NOAA/AOML) Shenfu Dong (NOAA/AOML; U. Miami)	Assessment of the Meridional Overturning Circulation and Meridional Heat Transport and their Meridional Variability in the South Atlantic Ocean	NASA	Jan 2013 – Dec 2016	93
Gustavo Goni (NOAA/AOML) Molly Baringer (NOAA/AOML) Sylvia Garzoli (NOAA/AOML)	The Ship of Opportunity Program	NOAA	Ongoing	
Ben Harden (WHOI) Robert Pickart (WHOI)	The Upstream Sources of the Denmark Strait Overflow	NSF	Sep 2014 – Aug 2016	93
Patrick Heimbach (MIT) Rui Ponte (AER) An Nguyen (MIT) Carl Wunsch (MIT)	An Eddy-Permitting Arctic and Sub-Polar State Estimate for Climate Research	NSF	Sep 2010 – May 2014	
Patrick Heimbach (MIT) Rui Ponte (AER)	Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period	NOAA	Aug 2010 – Jul 2014	94

PIs	Project	Sponsor	Duration	Page
Aixue Hu (NCAR)	Research Program on Modeling Future Climate Change: Effects of Increased Atmospheric Carbon Dioxide and Other Climate Forcings	DOE	Jan 2013 – Dec 2017	96
Bill Johns (U. Miami) Christopher Meinen (NOAA/AOML) Molly Baringer (NOAA/AOML)	Measuring Interannual Variability of teh AMOC and Meridional Ocean Heat Transport at 26.5N: The RAPID-MOCHA Array	NSF	Apr 2003 – Jun 2014	101
Kathryn Kelly (U. Washington) Suzanne Dickinson (U. Washington)	The Contributions of Ocean Circulation to North Atlantic SST	NASA	Feb 2010 – Jan 2015	103
Kathryn Kelly (U. Washington) LuAnne Thompson (U. Washington)	Assessing Meridional Transports in the North Atlantic Ocean	NASA	Oct 2008 – Mar 2014	
Kathryn Kelly (U. Washington) LuAnne Thompson (U. Washington)	Sources and Impacts of Variability of the Meridional Property Transports in the Atlantic Ocean	NASA	Jan 2013 – Dec 2016	105
Sergey Kravtsov (U. Wisconsin-Milwaukee) Anastasios Tsonis (U. Wisconsin-Milwaukee)	Decadal Variability of Interacting Climate Subsystems in the Northern Hemisphere	NSF	Jul 2014 – Jun 2017	107
Felix Landerer (Cal Tech/JPL) Katrin Bentel (Cal Tech/JPL) Carmen Boening (Cal Tech/JPL) Victor Zlotnicki (Cal Tech/JPL)	Variability of the South Atlantic Meridional Overturning Circulation	NASA	Jan 2013 – Dec 2015	110
Craig Lee (U. Washington) Jason Gobat (U. Washington) Kate Stafford (U. Washington)	The Arctic Observing Network at Critical Gateways—A Sustained Observing System at Davis Strait	NSF	Sep 2010 – Aug 2015	112
Susan Lozier (Duke U.) Bill Johns (U. Miami) Amy Bower (HWOI) Robert Pickart (WHOI) Fiamma Straneo (WHOI)	Overturning in the Subpolar North Atlantic (OSNAP)	NSF	Sep 2013 – Aug 2018	116
Christopher Meinen (NOAA/AOML) Sylvia Garzoli (U. Miami; NOAA/AOML) Renellys Perez (U. Miami; NOAA/AOML) Shenfu Dong (U. Miami; NOAA/AOML)	Southwest Atlantic MOC (SAM)	NOAA	Oct 2008 – Ongoing	118
Ceclie Penland (NOAA/ESRL) Douglas MacMartin (Cal Tech) Chesley McColl (CIRES; NOAA/ESRL) Leslie Hartten (CIRES; NOAA/ESRL) Eli Tziperman (Harvard U.)	Variability, Stochastic Dynamics, and Compensating Model Errors of the AMOC in Coupled IPCC Models	NOAA	Sep 2013 – Aug 2016	121
Renellys Perez (U. Miami; NOAA/AOML) Sylvia Garzoli (U. Miami; NOAA/AOML) Ricardo Matano (Oregon State U.)	South AMOC: Pathways and Modes of Variability	NOAA	Sep 2013 – Aug 2016	123
Renellys Perez (U. Miami; NOAA/AOML)	Variability of the South Atlantic Subtropical Gyre	NOAA	Apr 2014 – Mar 2017	125

PIs	Project	Sponsor	Duration	Page
Robert Pickart (WHOI) Michael Spall (WHOI)	Denmark Straight Overflow Water: A New Paradigm for the Origin of the Deep Western Boundary Current	NSF	Dec 2010 – Nov 2015	127
Robert Pickart (WHOI)	The Atlantic Water Boundary Current in the Eastern Arctic: Composition, Transport, Variability, and Dynamics	NSF	May 2013 – Apr 2017	128
Peter Rhines (U. Washington) Charles Eriksen (U. Washington)	Analysis of Eddies, Mixing, and Dense Overflows at the Iceland-Faroe Ridge in the Northern Atlantic Ocean Observed with Seagliders	NSF	Sep 2010 – Aug 2014	131
Peter Rhines (U. Washington) Sirpa Häkkinen (NASA/GSFC)	Improved Estimates of Atlantic Meridional Circulation from Altimetry with Tracers, Drifters, Gliders and Argo Floats	NASA	Jan 2013 – Dec 2016	133
Thomas Rossby (U. Rhode Island) Charles Flagg (Stony Brook U.)	The Norröna Project: An International Collaboration for Sustained Studies of the Meridional Overturning Circulation between Denmark, the Faroes and Iceland	NSF	Aug 2011 – Jul 2015	135
Irina Rypina (WHOI) Lawrence Pratt (WHOI)	Transport Pathways in the North Atlantic: Searching for Throughput	NSF	Mar 2012 – Feb 2015	137
Claudia Schmid (NOAA/AOML) George Halliwell (NOAA/AOML) Sudip Majumder (U. Miami)	Transport in the Upper Branch of the South Atlantic Meridional Overturning Circulation	NOAA	Aug 2014 – Jul 2017	138
Andreas Schmittner (Oregon State U.) Aixue Hu (NCAR) Sebasitan Mernild (LANL)	Modeling Effects of Greenland Ice Sheet Melting on AMOC Variability and Predictability	NOAA	Sep 2013 – Aug 2016	139
Uwe Send (UCSD/SIO) Matthias Lankhorst (UCSD/SIO)	Meridional Overturning Variability Experiment (MOVE)	NOAA	Jun 2005 – Ongoing	141
Michael Spall (WHOI)	Forced Transients in Water Mass Transformation and the Meridional Overturning	NSF	Sep 2012 – Aug 2016	142
Michael Spall (WHOI) Thomas Haine (Johns Hopkins U.)	Mechanisms of Freshwater Exchange Acress the East Greenland Shelf	NSF	Sep 2014 – Aug 2017	144
Fiamma Straneo (WHOI) Steven Lentz (WHOI)	From Rivers to the Ocean: The Dynamics of Freshwater Export from Hudson Strait	NSF	Apr 2008 – Mar 2014	
Fiamma Straneo (WHOI) Gordon Hamilton (U. Maine) David Sutherland (U. Washinton) Leigh Sterns (U. Kansas)	Glacier-Ocean Coupling in a Large East Greenland Fjord	NSF	Aug 2009 – Jan 2015	
Zoltan Szuts (U. Washington) Kim Martini (U. Washington)	Wave Processes Along 26ºN in the Atlantic	NSF	Mar 2014 – Feb 2017	144
John Toole (WHOI) Michael McCartney (WHOI) Ruth Curry (WHOI) Terrence Joyce (WHOI) William Smethie, Jr. (Columbia U./LDEO)	Line W: A Sustained Measurement Program Sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39N	NSF	May 2003 – Feb 2015	147

PIs	Project	Sponsor	Duration	Page
John Toole (WHOI) Magdalena Andres (WHOI) Ruth Curry (WHOI) Terrence Joyce (WHOI) Michael McCartney (WHOI) William Smethie, Jr. (Columbia U./LDEO)	Completing a 10-Year Record of Deep Western Boundary Current Observations at Line W: A Contribution to the AMOC Study	NSF	Mar 2014 – Feb 2018	147
Anastasios Tsonis (U. Wisconsin-Mikwaukee) Gregory Duane (U. Colorado) Joseph Tribbia (NCAR)	An Interactive Multi-Model for Consensus on Climate Change	DOE	Sep 2011 – Aug 2014	148
Edward Vizy (U. Texas-Austin) Kerry Cook (U. Texas-Austin)	Influence of the Equatorial Atlantic Cold Tongue and Angola Current on Atlantic Basin Climate Variability	NASA	Apr 2014 – Mar 2016	151
Chunzai Wang (NOAA/AOML)	Relationship of the Atlantic Warm Pool with the AMOC	NOAA	Sep 2011 – Aug 2014	152
Xiao-Hai Yan (U. Delaware) Young-Heon Jo (U. Delaware)	Satellite Multi-Sensor Studies of Deep Ocean Convection in the North Atlantic Ocean	NASA	Mar 2009 – Feb 2014	154
Jianjun Yin (U. Arizona) Steve Griffies (NOAA/GFDL) Shaoqing Zhang (NOAA/GFDL)	Signature of the AMOC in the North Atlantic Dynamic Sea Level	NOAA	Sep 2013 – Aug 2016	156
Rong Zhang (NOAA/GFDL)	Impact of AMOC on Arctic Sea Ice and Atmospheric Heat Transport into the Arctic	NOAA	Sep 2013 – ongoing	158
Rong Zhang (NOAA/GFDL) Jinting Zhang (U. Washington)	On the evolution of AMOC Fingerprints in the North Atlantic	NOAA	Jun 2013 – ongoing	159

Appendix C: Annual AMOC Project Reports

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

PIs: M. Baringer[1], S. Garzoli[2,1], G. Goni[1], and Shenfu Dong[2,1]
[1]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
[2]University of Miami, Miami FL

This project supports the development of a methodology to estimate heat transport variability using data collected along two high density expendable bathythermograph (XBT) transects operated by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), satellite data (altimeter and scatterometer), wind products from the National Center for Environmental Prediction (NCEP) 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.

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.

This year the meridional heat transport (MHT) in the South Atlantic was highlighted in three publications:

- Dong et al. (2014) examined observations from AX18 that suggest that the geostrophic transport plays an equal role to the Ekman transport in the AMOC seasonal variations at 34°S. This is different from the predominant control of the Ekman transport on the AMOC seasonality in the coupled climate models in the South Atlantic. Our results indicate that model biases in both the geostrophic and Ekman transports contribute to this difference. Compared to the observations, the models show stronger seasonal cycles in the Ekman transport and weaker seasonal cycles in the geostrophic transport.
- Baringer et al. (2014) extended this time series through 2013 and compared it to the ECCO2 state estimation model.
- Macdonald and Baringer (2013) compared the 35°S XBT derived meridional heat transport estimates to the estimates at 26°N and 41°N.

Ongoing analysis includes estimating the differences between *in situ* heat transport estimates and model-based estimates. In additional we are extending observational estimates to include satellite derived synthetic XBT profiles and hence longer monthly time series estimates along 20°S, 25°S, 30°S, and 35°S back to 1992.

An expansion of this program could include the analysis of all *in situ* data (not just XBT data) to determine the physical processes involved in meridional heat and mass transport throughout the Atlantic Ocean.

Online data

Heat transport estimates: http://www.aoml.noaa.gov/phod/soto/mht/index.php
XBT data: http://www.aoml.noaa.gov/phod/hdenxbt/index.php

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Dong, S., M. Baringer, G. Goni, C. Meinen, and S. Garzoli, 2014: Seasonal variations in the South Atlantic Meridional Overturning Circulation from observations and numerical models. *Geophys. Res. Lett.*, **41,** 4611-4618, doi:10.1002/2014GL060428.

Macdonald, A., and M. Baringer 2013: Ocean heat transport. *Ocean Circulation and Climate: A 21st Century Perspective*, G. Siedler, S. M. Griffies, J. Gould, and J. A. Church, Eds. International Geophysics Series, Volume 103, Academic Press, 759-785.

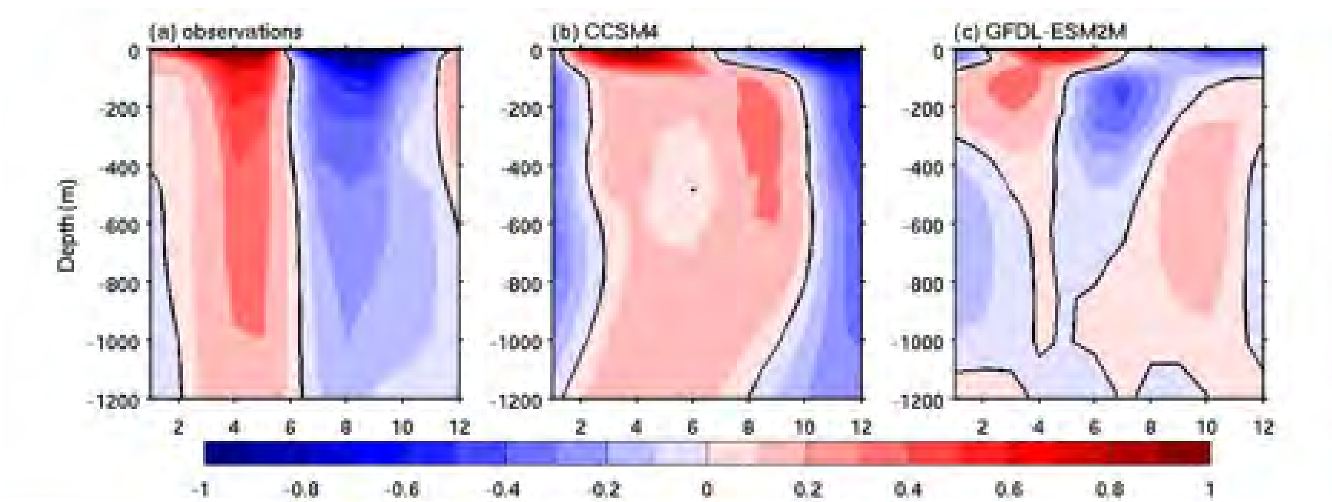

Figure 1: Month and depth distribution of zonally averaged meridional velocity along 34°S in the upper ocean computed from (a) observations and two CMIP5 models (b) CCSM4 and (c) GFDL-ESM2M. Time-mean values at each depth have been removed to better demonstrate the seasonal variations. Units are 10^{-3} m/s. One factor behind the strong seasonal cycle in the geostrophic transport from the observations is associated with the vertical coherence in the velocity signals below the mixed layer. The models lack this vertical coherence, showing strong baroclinicity below the surface mixed layer, yielding out-of-phase variations that sum to a very weak annual cycle in the geostrophic transports in the models.

Western Boundary Time Series

PIs: M. Baringer[1], C. Meinen[1], and S. Garzoli[2,1]
National Collaborators: B. Johns[2]
International Collaborators: D. Smeed[3], H. Bryden[3], E. Frajka-Williams[3], and S. Cunningham[4]
[1]NOAA Atlantic Oceanographic Meteorological Laboratory, Miami FL
[2]University of Miami, Miami FL
[3]National Oceanography Centre, Southampton, UK
[4]Scottish Marine Institute Oban, Argyll, 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 "ocean heat content and transport". The components include the northward flowing Florida Current and the southward flowing Deep Western Boundary Current.

Recent results

While this program only funds data collection this fiscal year the lead PIs published five papers on this data (Baringer et al. 2014a; Baringer et al. 2014b, Meinen and Garzoli 2014, Garcia and Meinen 2014, Smeed et al. 2014), and four data reports were published (Hooper and Baringer 2013b, Hooper and Baringer 2014a, Hooper and Baringer 2014c, Hooper and Baringer 2014d). The published papers included the following highlights:

- Baringer et al. (2014a) released the State of the Meridional Overturning Circulation report, which appeared in the State of the Climate Report and expanded the report to include 41°N, 26°N, and 16°N MOC transports as well as the Florida Current time series.
- Baringer et al. (2014b) released the State of the Meridional Heat Transport report, which appeared in the State of the Climate Report and included updated heat transport estimates from 41°N, 26°N and 35°S.
- Meinen and Garzoli (2014) published "Attribution of Deep Western Boundary Current variability at 26.5°N," which explores the mechanisms that cause large transport changes in the Deep Western Boundary Current (DWBC) east of the Bahamas and argues that the strongest variations are associated with Rossby wave-like features propagating westward from the interior that overwhelm the DWBC transport signal.
- Garcia and Meinen (2014) published "Accuracy of Florida Current volume transport measurements at 27°N using multiple observational techniques" that uses observations from a submarine cable, free-falling dropsonde floats, and lowered acoustic Doppler current profilers to quantify the precise accuracy of the Florida Current volume transport estimated and served to the public.
- Smeed et al. (2014) examined the first eight and a half years of the data from the 26°N MOC array to show a small but statistically significant downward trend in the MOC from the 26°N array, which is primarily resulting from changes in the ocean density structure within the basin interior. This change is likely to be associated with interannual and/or decadal variability, and it is superimposed on top of much stronger subannual variations that make extracting trends difficult. This illustrates the imperative need for making continuous daily estimates over long time scales in order to tease out these very important long-period signals.

Online data

NOAA Florida Current and cruise data: http://www.aoml.noaa.gov/phod/wbts/data.php
Merged with MOC data: http://www.noc.soton.ac.uk/rapidmoc/
Merged with Heat transport data: http://www.rsmas.miami.edu/users/mocha/

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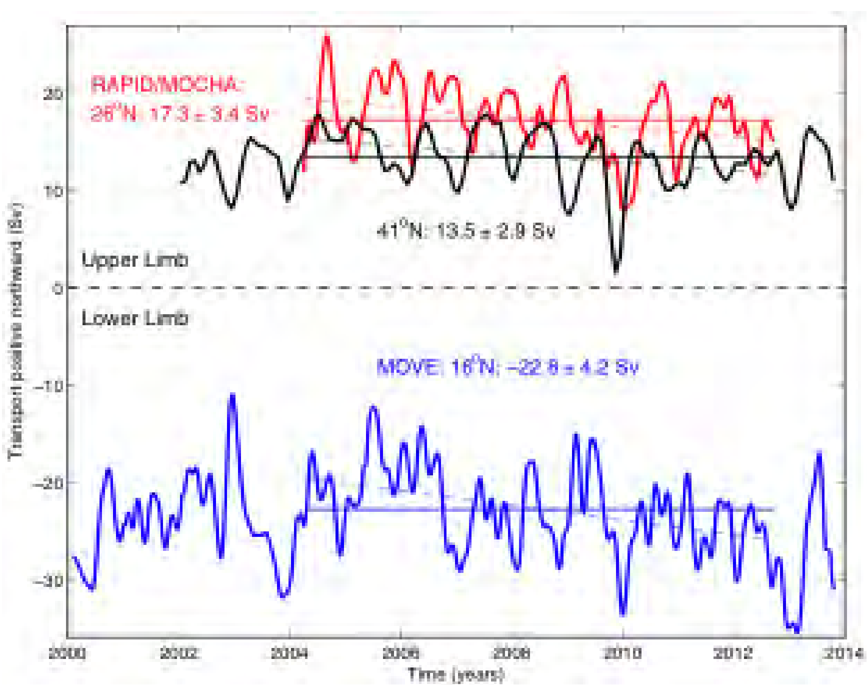

Figure 1: Baringer et al. (2014) show estimates of the MOC in the Atlantic Ocean from the Argo/Altimetry estimate at 41°N (black; Willis 2010), the RAPID-WATCH/MOCHA/WBTS 26°N array (red; Cunningham et al. 2007), and the German/NOAA MOVE array at 16°N (blue; Send et al. 2011) are shown versus year. All 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.

The Panularis Hydrographic Stations: Year 60-64

PIs: N. R. Bates[1], R. J. Johnson[1]
[1]Bermuda Institute of Ocean Sciences, St. Georges, Bermuda

The objective of this program is to observe the water column structure and time-series variability of North Atlantic Ocean waters near Bermuda at the nominal Hydrostation 'S' site (32° 10'N, 64° 30'W). This sustained ocean observation program has a frequency of 24 shipboard occupations of the Hydrostation 'S' per year. As of March 2014, we have 61 years of hydrographic data in hand from the time-series. Hydrostation 'S' data contributes to understanding of: (i) upper ocean physics, subtropical mode water, and climate connections in the North Atlantic subtropical gyre; (ii) deep water processes and Atlantic Meridional Overturning Circulation (AMOC); (iii) physical processes arising from measurements of gases and tracers; and (iv) biological processes and new production in the North Atlantic subtropical gyre. Funding for Hydrostation 'S' has been renewed until 2017.

Sampling program

The sampling program consists of two CTD hydrocasts per cruise (Sea-Bird SBE-09 CTD with an internal Digiquartz pressure sensor, a Sea-Bird SBE-03f temperature sensor, a Sea-Bird SBE-04 conductivity cell, and a Sea-Bird SBE-05 pump; Sea-Bird SBE-43 dissolved oxygen sensors, a *Wetlabs* deep transmissometer, a deep (6000m) *Chelsea Instruments* fluorometer and a *Biospherical* PAR sensor). The Sea-Bird CTD is mounted with a 24-position Sea-Bird model 32 rosette, which is equipped with 12L Ocean Test Equipment bottles, and wet salinity and Winkler dissolved oxygen measurements are also collected. Many other gas, tracer, and ocean biogeochemical measurements have and are being collected at Hydrostation S.

Recent results

For this current award, a total of 33 additional hydrographic stations have been performed at the nominal Hydrostation 'S' site increasing the total number of stations to 1255 as of October 1, 2014. All cruises during this current period were conducted on the R/V *Atlantic Explorer* with a station frequency ranging between 7 to 21 days and most stations consisted of two CTD casts. Hydrostation 'S' data have played a central role in understanding the seasonal and longer-term variations of hydrography and biogeochemistry in the Sargasso Sea as outlined in the four themes above (Schroeder et al. 1959; Menzel and Ryther 1960; Schroeder and Stommel 1969; Pocklington 1972; Talley and Raymer 1982; Jenkins 1982; Jenkins and Goldman 1985; Jickells et al. 1989; Joyce and Robbins 1996; Joyce and Talley 1996; Hazeleger and Drijfhout 1998, Curry et al. 1998; Joyce et al. 2000; Curry and McCartney 2001; Bates et al. 2002; Johnson 2003; Rossby et al 2005; Phillips and Joyce, 2006; Goodkin et al. 2008; Molinari 2011. Bates et al. 2012; 2014; IPCC, 2014). Several hundred papers have cited Hydrostation S data, and these papers have been cited more than 40,000 times.

Online data

The bottle salinity and dissolved oxygen data have been available at FTP site (ftp://batsftp.bios.edu/Hydrostation_S/). At this site users can access either the bottle data (one single file from 1955 to December 2011) or the individual CTD profiles from October 1988 to July 2012. Users can download both BATS and Hydrostation 'S' data from the interactive Matlab based web site http://www.bios.edu.

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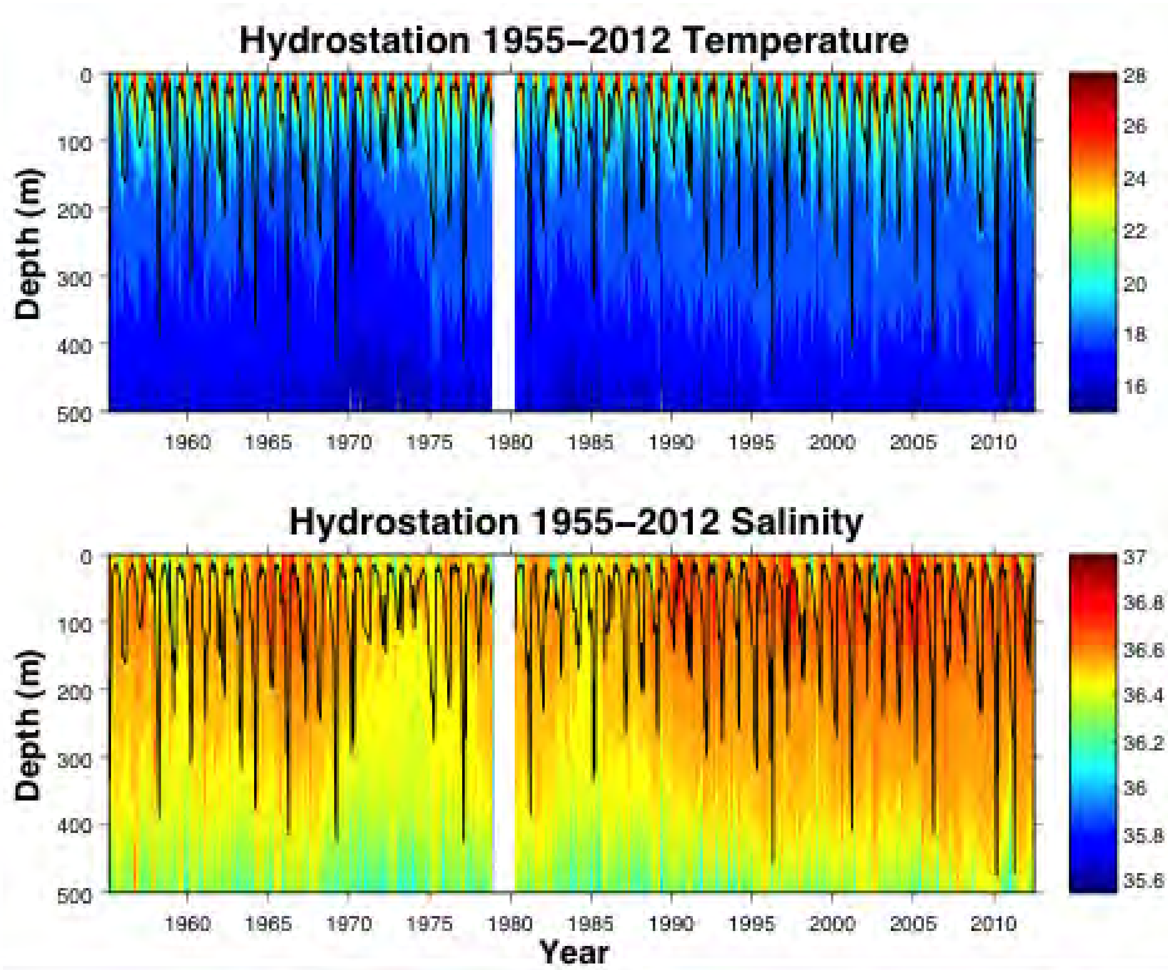

Figure 1. Contour plots of (top) temperature and (bottom) salinity for Hydrostation 'S' from January 1955 through July 2012. Mixed layer depth overlaid as the black line and is computed using the variable sigma__ method (Sprintall & Tomczak, 1992). The data gap from January 1979 through April 1980 represents the period where the hydrowire with all Nansen bottles and reversing thermometers was lost at sea and resources were not available for immediate replacement (Figure courtesy R. Johnson).

Crossroads of the Atlantic Meridional Overturning Circulation: The Charlie-Gibbs Fracture Zone

PIs: A. S. Bower and M. A. Spall
Woods Hole Oceanographic Institution, Woods Hole, MA

Introduction

While intense observational effort has recently been made to describe the basic structure and (in some cases) low-frequency variability at a few locations along the paths of the AMOC, relatively little attention has been paid to the Charlie-Gibbs Fracture Zone (CGFZ), a gateway for both the warm and cold limbs of the AMOC over the Mid-Atlantic Ridge. A combined observational and modeling study of the AMOC at the CGFZ is underway. An array of eight current meter and hydrographic moorings was installed across the CGFZ for two years beginning in July 2010 (with ship time provided by M. Rhein, University of Bremen) to measure the currents and water properties between the bottom and 500 m. This array provides the first long-term, simultaneous observations of both the westward and eastward flows over the CGFZ. This study will provide a transport benchmark for critical evaluation of climate models.

Recent results

All the mooring data has been processed and detailed descriptions are given in a data report published this year (Furey et al. 2014). These data were used to make a preliminary estimate of the record mean westward transport of Iceland-Scotland Overflow Water (ISOW) through the CGFZ, -1.7±0.2 (standard error) Sv, of which about two thirds was located in the northern transform valley (Figure 1). This is about 30% lower than an earlier one-year mean estimate from 1988-89 of -2.4±0.5 Sv (Saunders 1994). A preliminary analysis suggests that the difference is due mainly to the use of a fixed ISOW layer thickness in the earlier estimate (no temperature/salinity time series were available). If the new estimate holds up in the final analysis, a revision of the pathways of ISOW over the Mid-Atlantic Ridge may be required.

A simple model has been developed for the behavior of a western boundary current to the west of a mid-ocean ridge with a gap, such as for the CGFZ. The mean flow for strongly nonlinear flows resembles the linear flow pattern with boundary current separation to the west of the gap. However, a viscous sublayer produces anomalous potential vorticity, which is advected into the basin interior by the separated boundary current, resulting in a quasi-periodic state of westward propagating meanders in the interior and large meridional excursions of the separation point of the western boundary current. This is similar to what is observed for the East Australia Current near the southern tip of Australia and west of New Zealand. It is also consistent with the separation of the North Atlantic Current at the latitude of the CGFZ. A scaling theory for the amplitude and frequency of the oscillation is derived from consideration of the vorticity budget in the viscous sublayer and wave dynamics in the interior (Spall 2014). The influence of topography (islands, gappy ridges) on a strong zonal flow is now being explored using idealized numerical models and theory. Preliminary results suggest both standing and propagating wave patterns are possible with strong sensitivity to the location of the topography.

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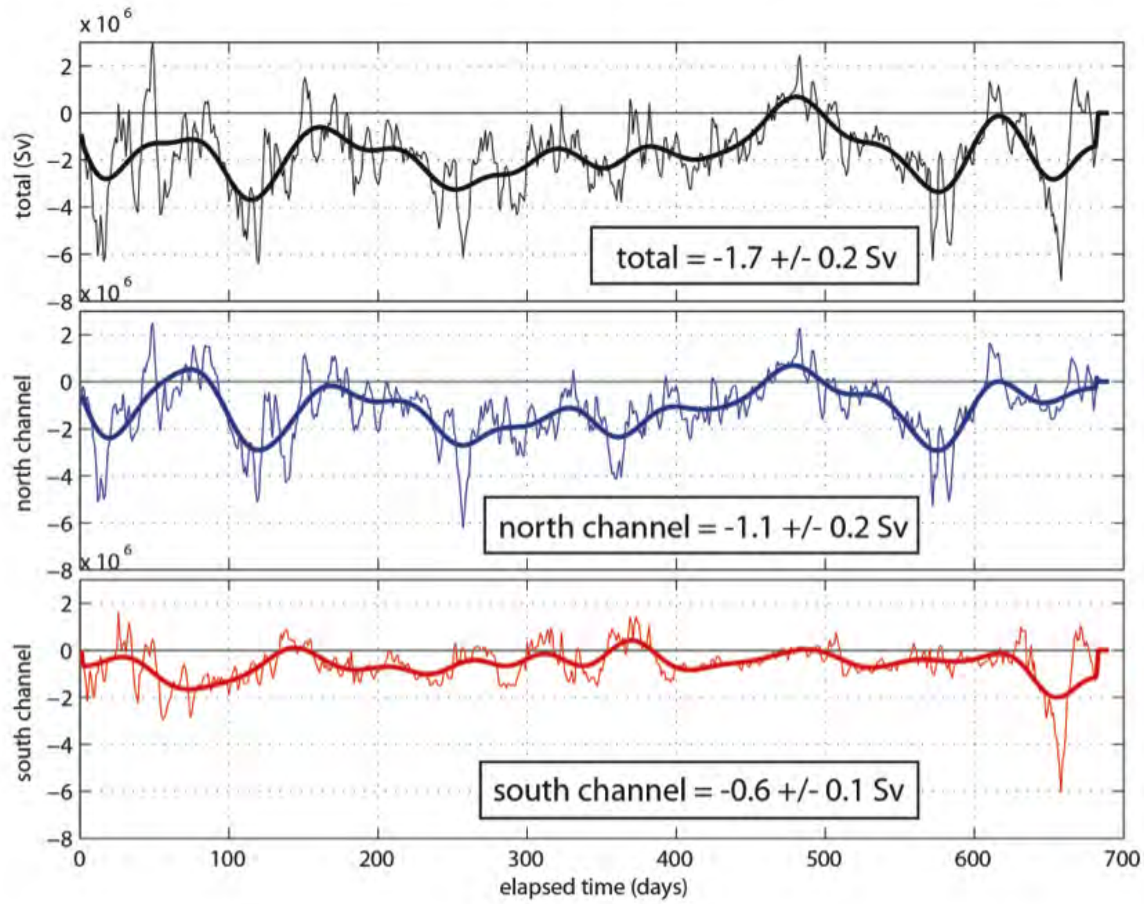


Figure 1: Two-year time series of ISOW transport through the CGFZ: total (upper), northern (middle) and southern (lower) transform valleys. Thin lines are daily averages and heavy lines are low-pass filtered with a 60-day cut-off period. As in Saunders (1994), there was significant low-frequency transport variability, including sign reversals.

Initial Value Predictability of Intrinsic Modes and Implications for Decadal Prediction over North America

PIs: G. Branstator[1], H. Teng[1], and G. Meehl[1]
International collaborators: A. Grisun[2]
[1]National Center for Atmospheric Research, Boulder, CO
[2]Institute for Numerical Mathematics/RAS, Moscow, Russia

The objective of this project is quantification of the predictability characteristics of the climate system as simulated by comprehensive climate models on decadal timescales. The focus is on the predictability of prominent or highly predictable patterns, and to determine whether the identified decadal predictability has a signature over North America.

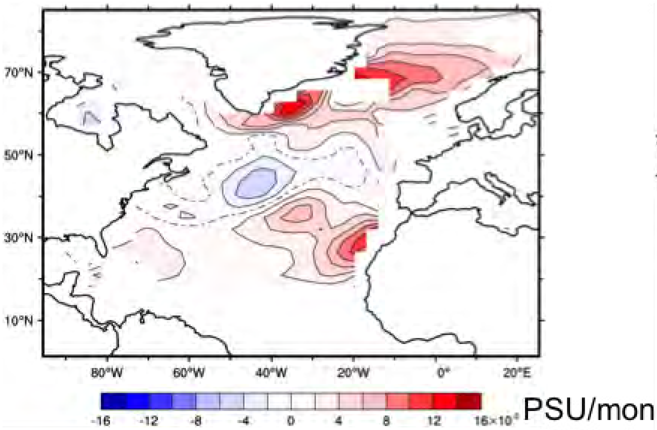
Recent results

During the early stages of this project we focused on predictability characteristics of coupled models that resulted from initializing them. Overall, we found that initialization, on average, had the potential to have a positive impact on the skill of predictions of AMOC and heat content for roughly a decade, but that this limiting range varied substantially from model-to-model as well as depending on the region one was predicting and whether annual or multi-year averages were being predicted. Of particular interest was the finding that there were special anomalous structures whose predictability was much higher than that of typical anomalies.

As a means of understanding some of the physical processes that might control the behavior of these special structures, we have focused on a new stage in this project that considers mechanisms by which the atmosphere may be involved in the production of high amplitude, long-lasting (and thus possibly highly predictable) ocean anomalies. To do this, we have developed a novel tool for efficiently determining the oceanic response of a coupled model to surface buoyancy and momentum fluxes of arbitrary structure. Using this tool we are able to find the most efficient geographical distribution of fluxes for producing a large AMOC or heat content response at a given range. The theoretical basis for developing this tool is the fluctuation dissipation theorem, which is an idea borrowed from statistical physics. The theorem states that the response of dynamical systems with certain reasonable properties can be found by simple matrix multiplication of a (sufficiently weak) forcing vector times a linear response operator whose elements depend only on lag-covariance statistics of the undisturbed system.

In the past year, we have extensively tested the fluctuation dissipation theorem when it is applied to a low-resolution version of CCSM4 and found that it can be used to make good estimates of the GCM's oceanic response to salinity, temperature, and momentum near-surface forcing. Given this success, we have then used it to find the most efficient way to force anomalous AMOC circulations. An example is given in Figure 1, which shows the salinity-forcing pattern (left panel) that produces the strongest AMOC response (right panel) after the forcing has been applied for five years. The structure of this optimal response pattern is very similar to the leading EOF of multi-year AMOC variability. Optimal patterns of temperature and momentum forcing also produce a similar AMOC response. For both forms of buoyancy forcing the regions that are most efficient at exciting AMOC are also the regions in the Nordic Seas where deep convection is most common in this version of CCSM4. Our previous results indicate that this same pattern of AMOC variability is highly predictable, and the current results indicate forcing by the atmosphere may be involved in the initiation of these highly predictable events. Also of interest is that this pattern is so much easier to excite than are typical

AMOC anomalies that no special atmospheric patterns (e.g. the NAO) are necessary to explain its prominence. Even random fluxes produced by random atmospheric variability would produce the amount of AMOC EOF1 variability observed in CCSM4.



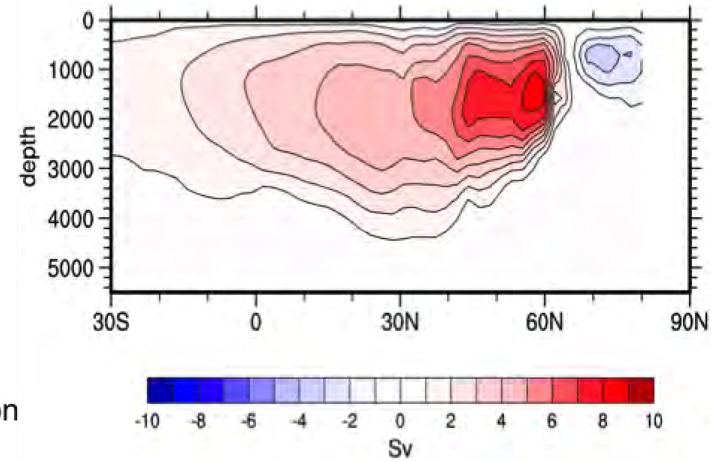


Figure 1. Salinity forcing (left) that produces the maximum AMOC response (right) when applied for 5 years to the near surface layer of CCSM4, as calculated using the fluctuation dissipation theorem.

Identifying Mechanisms of AMOC Variability in ECCO State Estimates and CMIP5 Models

PIs: M. W. Buckley[1] , P. Heimbach[2], R. M. Ponte[3] and J. Furtado[3]

[1]George Mason University, Fairfax, VA

[2]Massachusetts Institute of Technology, Cambridge, MA

[3]Atmospheric and Environmental Research, Lexington, MA

Over the past year, our project has focused on two main science questions: (1) determining the relative roles of atmospheric forcing and ocean dynamics (e.g., Rossby waves, changes in the gyre circulations and/or AMOC) in setting upper-ocean heat content (UOHC) variability in the North Atlantic and (2) exploring mechanisms of decadal AMOC variability originating from the North Atlantic basin. Thus far, our main tool has been data-constrained, dynamically and kinematically consistent estimates of the global circulation produced by Estimating the Circulation and Climate of the Ocean (ECCO).

Relationship between AMOC and UOHC variability

Our goal is to determine the portion of North Atlantic UOHC variability that is due to active ocean dynamics, such as the AMOC. To explore this question, we utilize the ECCO state estimate (1992-2011) to quantify the upper ocean heat budget in the North Atlantic on monthly to interannual timescales (seasonal cycle removed). Three novel techniques are introduced: (1) the heat budget is integrated over the maximum climatological mixed layer depth (integral denoted as H), which gives results that are relevant for explaining SST while avoiding strong contributions from vertical diffusion and entrainment; (2) advective convergences are separated into Ekman and geostrophic parts; and (3) air-sea heat fluxes and Ekman advection are combined into one "local forcing" term. In the interior of the subtropical gyre, the sum of air-sea heat fluxes and Ekman heat transport convergences is a reasonable measure of local atmospheric forcing, and such forcing explains the majority of H variability on all timescales resolved by ECCO. In contrast, the Gulf Stream region and subpolar gyre have ocean dynamics that are found to be important in setting H on interannual timescales. Air-sea heat fluxes damp anomalies created by the ocean and thus are not set by local atmospheric variability.

These results suggest that the AMOC does not play an active role in setting UOHC anomalies in the subtropical gyre on the timescales resolved by the ECCO estimate. In contrast, ocean dynamics, perhaps including ocean heat transport (OHT) convergence variability due to AMOC variability, play a role in setting UOHC in the Gulf Stream region and the subpolar gyre. Whether these results hold at longer timescales is a subject of our present work using CMIP5 models.

Mechanisms of decadal AMOC variability

Currently there is no accepted mechanism for decadal AMOC variability and little background theory on which the community agrees. Insights about mechanism have largely come from models, but the magnitude and time scale of AMOC variability varies markedly across models and model formulations. Despite this, there are three robust features of AMOC variability that may inform mechanisms of decadal variability. (1) Observations and models suggest that buoyancy anomalies on the western boundary are key to understanding low-frequency AMOC variability. (2) A pacemaker region for decadal AMOC variability appears to be located along the boundary between the subtropical and subpolar gyres. (3) Meridionally coherent decadal AMOC anomalies are communicated southward from this pacemaker region. We use these three robust features to argue that the region near the Grand Banks where the Gulf Stream/North Atlantic Current and the deep western boundary current cross over, henceforth called the transition zone (TZ). The TZ is a key region influencing large-scale decadal AMOC variability. Processes that are important in creating buoyancy anomalies in the TZ are expected to play an important role in AMOC variability. Such processes include local atmospheric forcing, advection of anomalies by mean currents, westward propagating baroclinic Rossby waves, anomalies resulting from large-scale ocean circulation changes (such as shifts of the Gulf Stream path), and anomalies advected/propagated from high latitudes. The complex ocean dynamics in the TZ likely explain why AMOC variability is so sensitive to model formulation, both between models and in the same model when changes are made to its resolution, overflow parameterizations, etc.

We are currently investigating decadal variability of the AMOC in the ECCO v4 model, and relating it to variability in the TZ region. Furthermore, we have conducted an UOHC budget over the TZ in order to assess the processes that are important in setting UOHC variability in this key region (see Figure 1). We find that geostrophic currents (eddy and mean) dominate temperature variability on interannual timescales, while local air-sea heat flux and Ekman mass transport variability dominate on intra-annual timescales.

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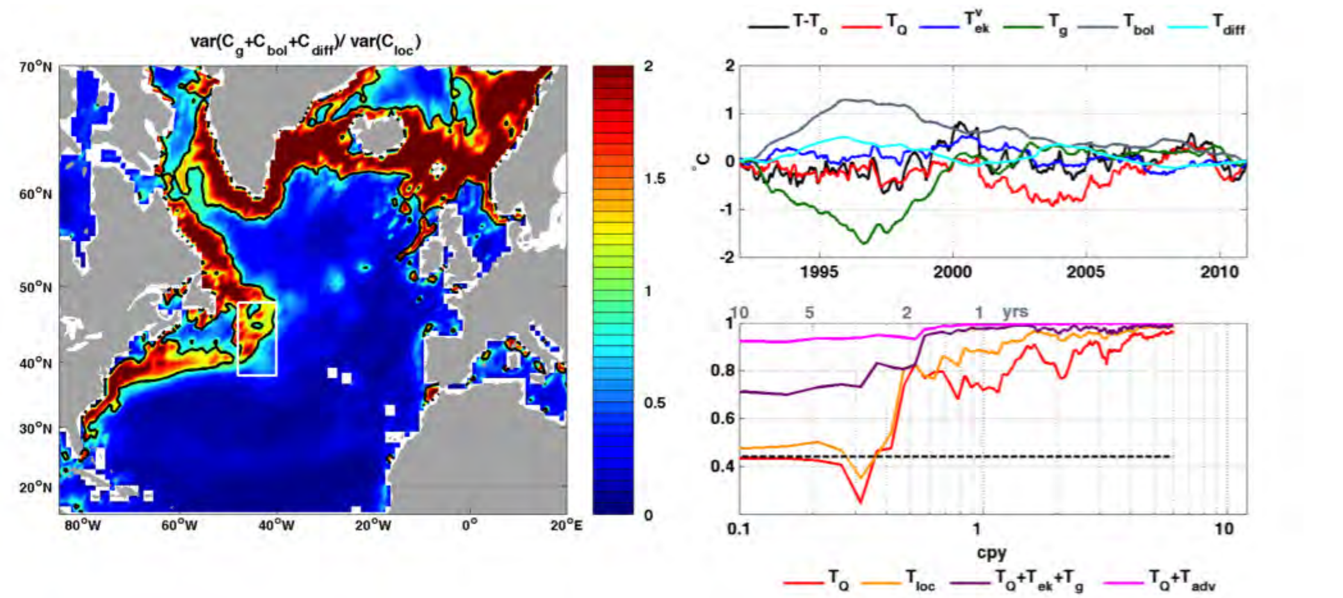

Figure 1. A heat budget analysis over the maximum climatological MLD using ECCO v4. (left) Map shows the ratio of the variance of convergences due to ocean dynamics (Cg+Cbol+Cdiff, geostrophic, bolus, and diffusive convergences, respectively) to convergences due to local forcing (Cloc). The ratio is small over the gyre interiors, but large over boundary currents and the TZ region. (right) The temporally integrated heat budget over the TZ (white box in left panel). (top right) Time series of temperature (T-To), air-sea heat fluxes (TQ), convergence due to Ekman mass transport variability (Tek^v), geostrophic convergences (Tg), bolus convergences (Tbol), and diffusive convergences (Tdiff). The advective convergence (Tadv) is separated into the linear advective convergence (Tlin) and Tbol and Tek+Tg ≈Tlin. (bottom right) Magnitude of the coherence between T-To and various sums of terms in the T budget.

Using Ocean Data Assimilation to Explore Arctic/Subarctic Climate Variability

PIs: J. Carton[1], G. Chepurin[1], S. Häkkinen[2], and M. Steele[3]
[1]University of Maryland, College Park, MD
[2]NASA Goddard Space Flight Center, Greenbelt, MD
[3]University of Washington, Seattle, WA

Recent results

- Completed publication of the meeting report from the 2013 US AMOC-UK Rapid science meeting (Carton, et al. 2014)
- Made progress on upgrade of the Simple Ocean Data Assimilation (SODA) ocean reanalysis, which provide long-term estimates of AMOC and related meridional heat transports.
- Adoption of a new ocean/sea ice model based on GFDL MOM5.1 numerics (provisional name: SODA3.1).

- Development of a hybrid (ensemble/3DVAR) data assimilation filter as an eventual replacement for the data assimilation currently being used in SODA. The algorithm was published last year, a study using idealized data is under review (Penny et al. 2015*)* and an experiment using real (historical data) is being carried out now.
- Made progress on Arctic climate variability in CMIP-type coupled climate models. The student Yanni Ding completed her dissertation on this subject. The title of her dissertation is: Ocean Variability in CMIP5 Historical Simulations. The first paper on the response of the ocean to volcanic aerosols was published this year (Ding et al. 2014). The other studies are being prepared for publication.

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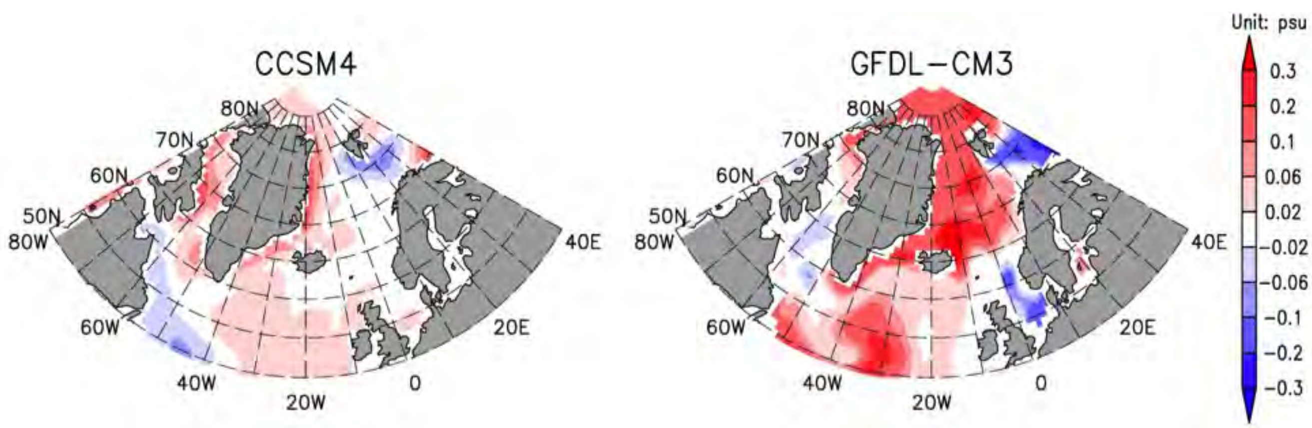

Figure 1. This is a figure from Ding et al. (2014*)* and shows the change in surface salinity (SSS) in the North Atlantic due to the eruption of Krakatoa as represented in ensembles of two widely used CMIP5 coupled climate models. CCSM4 shows a weak impact on SSS and as a consequence the eruption has little impact on the strength of AMOC. In contrast GFDL-CM3 shows a strong impact on SSS and a strong (up to 3Sv) strengthening of AMOC.

Submarine Melting and Freshwater Export in Greenland's Glacial Fjords: The Role of Subglacial Discharge, Fjord Topography and Shelf Properties

PIs: C. Cenedese[1], F. Straneo[1], and P. Heimbach[2]
[1]Woods Hole Oceanographic Institution, Woods Hole, MA
[2]Massachusetts Institute of Technology, Cambridge, MA

Increased submarine melting of Greenland's glaciers has emerged as a plausible trigger for their recent acceleration and for quadrupling Greenland's contribution to sea level rise from 1992-2000 to 2001-2011. Notwithstanding its importance, our understanding of submarine melting is limited and it is presently absent or crudely parameterized in glacier, ice sheet, and climate models. Ocean models are beginning to include freshwater discharge from Greenland, but where and when this freshwater enters the continental shelves is largely unknown. Understanding the dynamics that govern both submarine melt and freshwater fluxes, including their magnitude and spatial distribution, is a key step in projecting sea level rise and the consequences of the Greenland-induced ocean freshening.

Intellectual merit

The exchange of heat and freshwater between the ocean and Greenland's outlet glaciers, typically grounded hundreds of meters below sea level, occurs at the head of long, deep fjords that connect the ice sheet margins to the continental shelves and the large-scale North Atlantic circulation. Recent work by the PIs, and others, has shown, for several idealized or specific cases, that the fjord's temperature and stratification, as well as the summer discharge of surface melt at the base of the glacier (subglacial discharge) have a first order impact on the magnitude, distribution, and timing of submarine melting. We propose to generalize these results by formulating parameterizations, suitable for large-scale ice sheet and climate models, of submarine melting and associated freshwater export distributions as a function of large-scale controls. Specific tasks are:

- Establishing dynamical links between submarine melting, and the associated freshwater export from the glacier, and its dominant controls, which include: the magnitude and spatial distribution of subglacial discharge; hydrographic properties and stratification on the continental shelf; and fjord size and topography, in particular the presence and height of a sill.
- Formulating two complementary parameterizations: one for the magnitude and spatial distribution of submarine melting as a function of the fjord's topography and size, the shelf stratification and the subglacial discharge, to be used in glacier and ice sheet models; and one for the magnitude and vertical distribution of the freshwater export from the fjords to be used in large-scale ocean and climate models which do not resolve the fjords.

This project involves the analysis of existing data, laboratory experiments, and high-resolution numerical simulations. It will be carried out in collaboration with two international experts: a glacial hydrologist (I. Hewitt, U. of Oxford) and a fjord oceanographer (L. Arneborg, U. of Goteborg). The work is aimed at understanding a newly discovered 'wiring' of our climate system and is timely because of the large and unanticipated changes that are occurring at Greenland's margins. It is complementary to the study of ice sheet/ocean interactions around Antarctica (the more studied of the two) since both the large-scale ocean circulation and the presence of narrow, long fjords in Greenland contribute a unique set of relevant dynamical mechanisms.

Broader impacts

This work seeks to increase our understanding of a previously overlooked, important connections in our climate system, which has profound implications for our ability to project sea level rise – an issue of grave and immediate societal concern. It is expected that results from this work will contribute to the inclusion of the relevant dynamics (even if in parameterized form) in future models and, as such, lead to the improvement of future sea level projections. The work plan involves international experts from complementary fields and will contribute to fostering interactions between the multiple disciplines involved and beyond national boundaries. It involves one student and one post-doc who will be exposed to a cutting-edge problem and a multidisciplinary team of researchers. Results from this work will be widely disseminated to scientists across disciplines, as demonstrated by the PIs long track record of organizing summer schools and working groups, and to the public through different media outlets, including a blog on polar science. Recent Greenland related work by the PIs has been featured in the New York Times, the Weather Channel, and Italian National Television, amongst other media.

Multiple Equilibria and Low-Frequency Variability in the Adiabatic Overturning Circulation

PIs: P. Cessi and C. L. Wolfe
Scripps Institution of Oceanography, La Jolla, CA

Our project is concerned with the Atlantic Meridional Overturning Circulation (AMOC), its stability, variability, and sensitivity to atmospheric forcing, both mechanical (wind-stress) and thermodynamical (heat and freshwater surface fluxes). The focus is the interhemispheric cell in the largely adiabatic regime, where the flow is characterized by a descending branch in the high latitudes of the North Atlantic and the upwelling branch in the Antarctic Circumpolar Current (ACC) region of the Southern Ocean. These two end points are connected by shared isopycnals along which the flow takes place.

The approach is to systematically study the amplitude and frequency of the AMOC's response to localized buoyancy with a coarse-resolution ocean-only model in a domain of simple geometry: a single semi-enclosed basin spanning two hemispheres of equal extent, with the southernmost eighth of the domain consisting of a reentrant channel periodic in longitude. We analyze the model using innovative diagnostics, focused on the residual overturning circulation (ROC), which is the proper measure of the transport of heat and other tracers.

Recent results

- In the limit of weak interior mixing, the ocean can support a pole-to-pole overturning circulation on isopycnals that outcrop in both the Northern Hemisphere and a high-latitude southern circumpolar channel. This overturning cell participates in a salt feedback, which counteracts the precipitation-induced surface freshening of the northern high latitudes without substantially affecting the southern high-latitude salinity. The net result is an increase in the range of isopycnals shared between the two hemispheres, which strengthen the overturning circulation. This process results in a positive salt feedback.

- If precipitation in the Northern Hemisphere sufficiently exceeds that in the Southern Hemisphere, the overturning cell reverses and its southern end-point moves equatorward of the channel. The reversed overturning circulation is shallower and weaker than its forward counterpart and is maintained diffusively. In a limited range of parameters, multiple equilibria are found for the same forcing configuration.
- For weak diapycnal diffusivity, the multiple equilibria are unstable to time-dependent oscillations around each of the fixed points. The oscillations around the forward cell peak at a decadal timescale with a mode expressed in the Northern Hemisphere subpolar gyre, modulated by a multi-centennial oscillation occupying both hemispheres. These oscillations mediate transitions between the multiple regimes.

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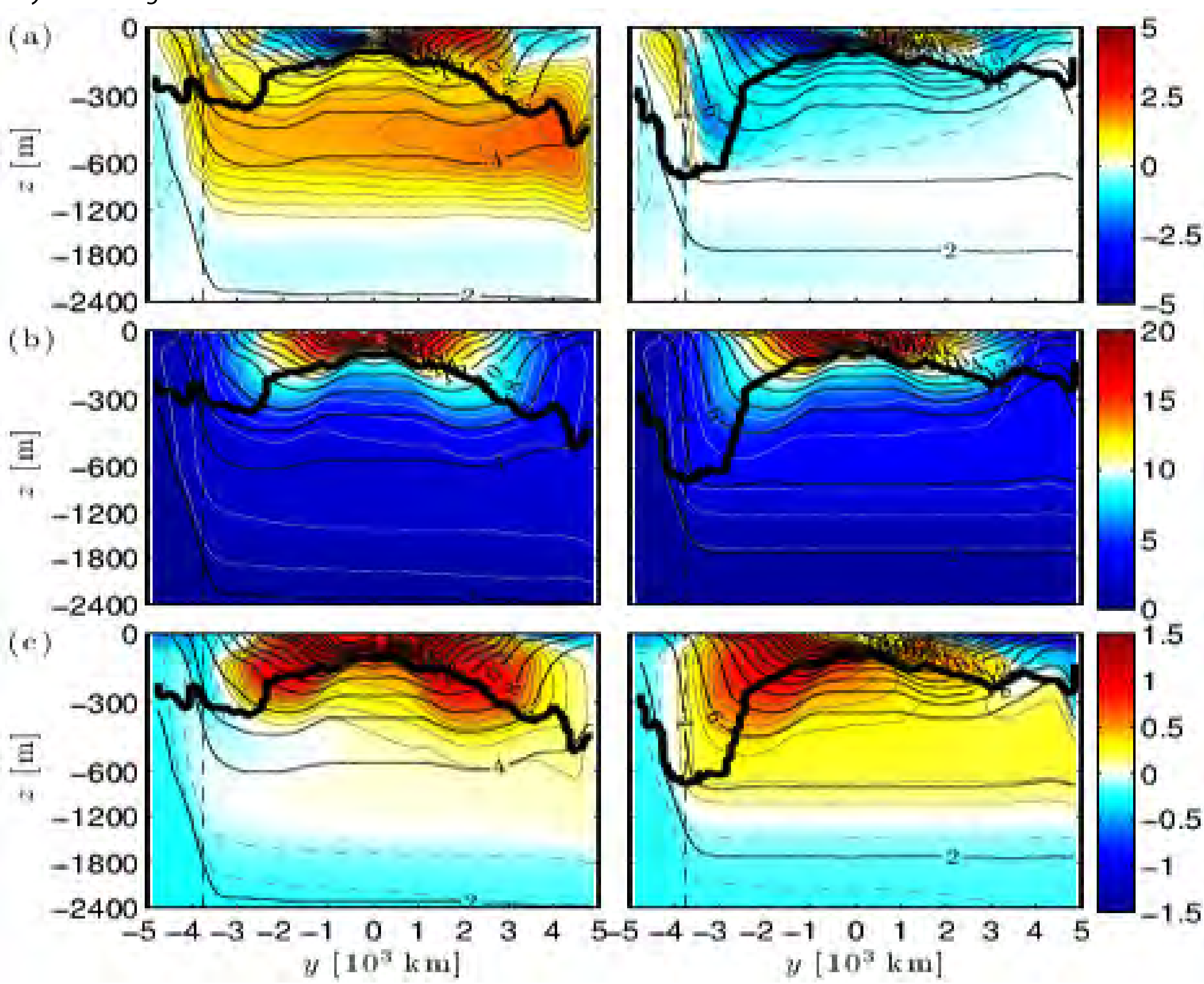

Figure1. (a) Zonally averaged overturning streamfunctions (colors/thin lines with interval 0.25 Sv) and zonally averaged buoyancy (thick lines, in units of $10m^{-3}s^{-2}$) for the forward (left panel) and reversed (right panel) cases. Both solutions are found for the same of external parameters, but different initial conditions. The thick dashed line gives an estimate of the base of the mixed layer. A vertical dashed line denotes the northern edge of the channel. (b) The corresponding temperature values (averaged zonally on buoyancy surfaces). (c) The corresponding salinity (averaged zonally on buoyancy surfaces).

Role of Atmospheric Internal Variability in the Atlantic Meridional Overturning Circulation

PIs: P. Chang[1], L. Ji[1], and B. Kirtman[2]
[1]Texas A&M University, College Station, TX
[2]University of Miami, Miami, FL

The objectives of this program are 1) to explore the role of atmospheric internal variability (AIV) in both natural variability and forced change of the AMOC and 2) to close the gap in understanding the linkage between the AMOC and the Atlantic Multidecadal Oscillation (AMO) in the context of understanding AMOC's role in the global climate system.

Recent results

Our research over the past year has focused on the relationship between synoptic winter atmospheric variability and modes of climate variability in the North Atlantic, as well as their interactions with ocean circulations in the North Atlantic. Using atmospheric reanalysis datasets, including NCEP-CFSR, NCEP-NCAR, NOAA 20th century reanalysis data, and the observationally derived OAflux dataset, we analyzed boreal winter (November thru March) extreme flux events in the Gulf Stream Region (GSR). These extreme flux events, most of which last less than three days, are characterized by cold air outbreaks with an anomalous northerly wind that brings cold and dry air from the North American continent to the GSR. A close relationship between the extreme flux events over GSR and the East Atlantic Pattern (EAP) is found with more frequent occurrence of the extreme flux events during a positive EAP phase and vice versa. Interestingly, the North Atlantic Oscialtion is closely related to the extreme flux events in the Labrador Sea region. A further lag-composite analysis suggests that the EAP may be explained as a rectified effect of the synoptic winter storms accompanied with the extreme flux events and that the event-day storms tend to have a preferred southeastward propagation path over the North Atlantic, potentially contributing to the southward shift of the storm track over the eastern North Atlantic basin during EAP positive phase. A similar relationship is found between the extreme flux events over the Kuroshio extension region and the Pacific Decadal Oscillation. A paper summarizing these results has been submitted to *Journal of Climate*. Currently, we are investigating how much this synoptic winter atmospheric variability can impact the AMOC.

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Understanding Changes in the Atlantic Meridional Overturning Circulation During the 20th Century Using IPCC AR5 Model Ensembles

PIs: P. Chang[1], S. Yeager[2], and G. Danabasoglu[2]
[1]Texas A&M University, College Station, TX
[2]National Center for Atmospheric Research, Boulder, CO

The objectives of this collaborative research between TAMU 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 (Inter-governmental Panel on Climate Change Fifth Assessment Report) 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 IPCC AR5 coupled climate model simulations and 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

We have compared the representation of the Atlantic Multidecadal Variability (AMV) over the 20th century in the 30-member Community Earth System Model Large Ensemble (CESM-LE) simulations to that simulated in a forced ocean—sea ice simulation (Figure 1). The latter experiment is forced with the Coordinated Ocean-ice Reference Experiments inter-annually varying atmospheric data sets (CORE-II) for the 1948-2007 period (Danabasoglu et al., 2014) and is referred to as the CORE-II POP (Parallel Ocean Program). The forced simulation shows excellent agreement with observations (HADISST; Rayner et al. 2003) over the latter half of the 20th century, and we find that the CESM-LE ensemble-mean AMV also exhibits a reasonable reproduction of relatively warm conditions around mid-century and in the 1990s, with relatively cool conditions in the 1960s and 1970s. The existence of such a decadal AMV signal in the CESM-LE ensemble-mean, which is consistent with observations, suggests an important role for external forcing in the AMV variations of the 20th century. However, analysis of surface heat fluxes, averaged over the North Atlantic, indicates that the CESM-LE AMV signal is largely driven by net shortwave and longwave downwelling radiation. This stands in contrast to the CORE-II POP in which ocean circulation changes linked to AMOC play a dominant role in the decadal sea surface temperature (SST) variability in the Atlantic (Yeager and Danabasoglu 2014). The pattern of late 20th century SST warming in CESM-LE is broadly distributed over the whole Atlantic, whereas in the observations and forced hindcast, the warming is concentrated in the North Atlantic along the Gulf Stream and its extension into the subpolar gyre (Figure 2). The CESM-LE warming in Figure 2 is associated with a large and uniform increase in downwelling longwave radiation (not shown), but we find that the realistic AMV signal in CORE-II POP is almost identically reproduced even when the radiative surface heat fluxes are replaced with climatology (Figure 3, experiment POPTurb). Thus, the correspondence between the AMV signal in CESM-LE and the observed AMV appears to be coincidental with different mechanisms at work in CESM-LE than in CORE-II POP. In particular, heat flux appears to be the dominant AMV driving mechanism in CESM-LE whereas AMOC is the key driver in CORE-II POP. Work is ongoing to partition AMV mechanisms in the individual ensemble members of CESM-LE.

In other collaborative work, we are investigating the sudden onset of the 2007/8 deep convection in the Labrador Sea (LS), which has been hypothesized to be related to the intensified winter storm activity in the region (Vage et al. 2009). To test this hypothesis, a series of CORE-II forced ocean—sea ice sensitivity experiments has been conducted, where either the CORE-II forcing has been manipulated to examine the relative importance of various atmospheric variables in affecting the deep convection or the oceanic initial condition between the 2006/7 and 2007/8 winters has been switched to test the importance of ocean pre-conditioning for deep convection. The modeling results show that the onset of the LS deep convection in the 2007/8 appears to be more attributable to low-frequency atmospheric anomalies than synoptic storm activities. In comparison to the 2006/7 winter, the 2007/8 winter features a stronger atmospheric pressure gradient across the LS, which brought cold air from the Arctic by the westerlies and created a favorable condition for deep convection over the LS. A journal publication summarizing these results is currently in preparation.

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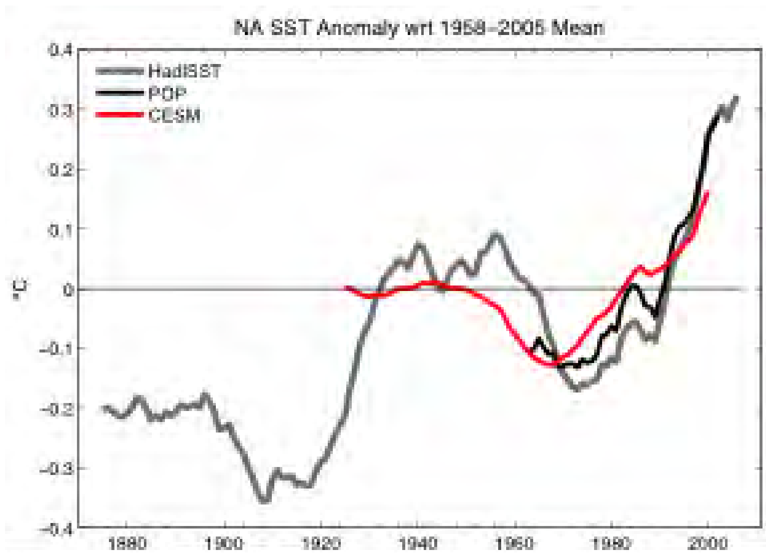

Figure 1. Time series of smoothed North Atlantic SST anomaly from the CESM-LE ensemble mean (red curve), the CORE-II POP simulation (black curve), and HADISST observations (grey curve).

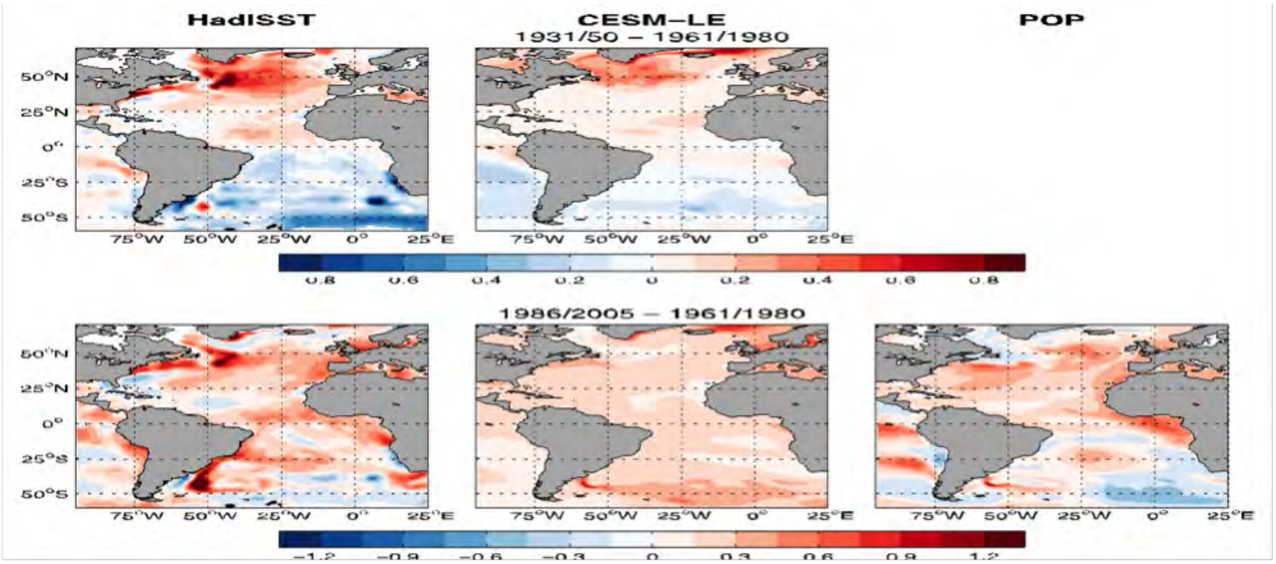

Figure 2. Differences in 20-yr mean SST averaged over the AMV warm period (1986-2005) and the AMV cool period (1961-1980) as seen in Figure 1: (left) HadISST observations, (middle) CESM-LE, and (right) CORE-II POP.

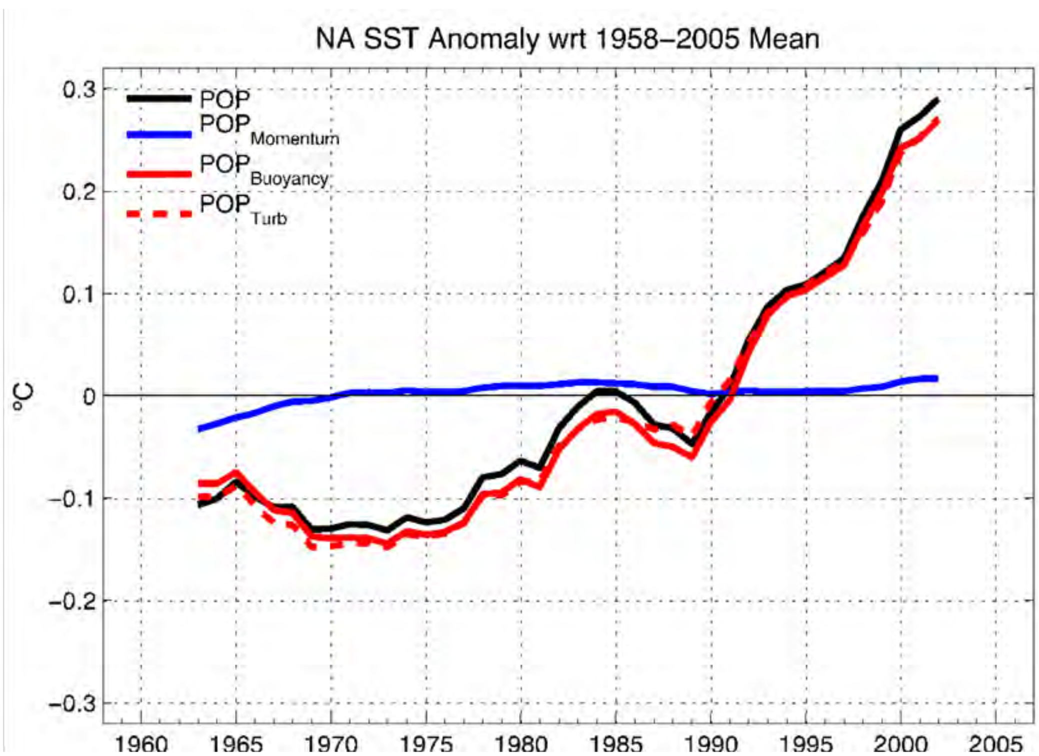

Figure 3. AMV from CORE-II POP (black curve) decomposed into momentum-forced (POPM; blue curve) and buoyancy-forced (POPB; red curve) components following Yeager and Danabasoglu (2014). A variant of POPB in which only turbulent buoyancy fluxes are allowed to vary interannually is given by POPTurb (red dashed curve). In that experiment, shortwave and downwelling longwave radiation does not vary from year to year, and yet the AMV signal is almost wholly recovered.

High-Resolution Model Development to Quantify the Impact of Icebergs on the Stability of the AMOC

PIs: A.Condron and R. Bradley
University of Massachusetts, Amherst, MA

This project has developed a sophisticated iceberg model (MITberg) to more accurately evaluate changes in the cryosphere on ocean circulation, climate, and in particular the Atlantic meridional overturning circulation (AMOC). MITberg has been successfully coupled to MITgcm ocean-sea ice model and integrated at eddy permitting resolutions (~1/6°; 18 km). This has allowed a detailed study of the interaction between meltwater/icebergs with open ocean convection and North Atlantic Deep Water (NADW) formation. In 2013, we implemented a keel model into the iceberg model code, allowing icebergs to assume a variety of shapes both above and below the waterline. This routine was develop as a 'multilevel' drag scheme to account for water drag at different vertical levels in the water column, and was found to produce increasingly realistic iceberg drift patterns (Figure 1a). Additional simulations focused on reproducing the historic record of iceberg drift collected at 48°N that began in 1900.

A second focus of 2013 was the development of the first ever eddy-permitting ocean-sea ice-iceberg model simulation of the last ice age, 21,000 years ago (Figure1b). Using this new set up, we showed that icebergs and meltwater discharged from the Laurentide ice during glacial times would have first been transported to the subtropical gyre, not the subpolar gyre, by narrow coastal boundary currents (Figure1c). This meltwater was advected northwards by the Gulf Stream to regions of NADW formation over a period of several decades, producing a delayed, more muted response, in deepwater formation to increased high-latitude freshwater forcing, compared to the more traditional freshwater hosing experiments. A fraction of icebergs and meltwater penetrated south of Cape Hatteras and under the right forcing conditions carried massive (up to 300 m thick) icebergs to southern Florida. This transport pathway is supported by the discovery of iceberg scours in equivalent water depths along the entire US continental shelf from Newfoundland to Florida Keys (Figure 1d). This research was published in *Nature Geoscience* in October 2014.

Recent results

- To accurately simulate iceberg drift one must account for water drag forces at all levels in the water column (not just the surface) that an iceberg keel penetrates. Moving towards higher ocean model resolutions that simulate mesoscale eddies and narrow coastal currents also help to produce increasingly realistic iceberg distributions.
- During glacial periods the Gulf Stream was more zonal, with limited transport of heat to northern Europe and the Arctic. An expansion of the cold, fresh, subpolar gyre led to increased eddying at the subpolar-subtropical gyre boundary due the larger thermal gradient in this region.
- Large meltwater floods from Hudson Bay were capable of transporting Northern Hemisphere icebergs as far south of Florida Keys. A more subtropical meltwater-iceberg pathway (compared to the traditional 50°N-70°N hosing zone) has implications for understanding how increases in high-latitude freshwater forcing from the Greenland ice sheet will influence subpolar deep water formation and the strength of the AMOC in the near-future.

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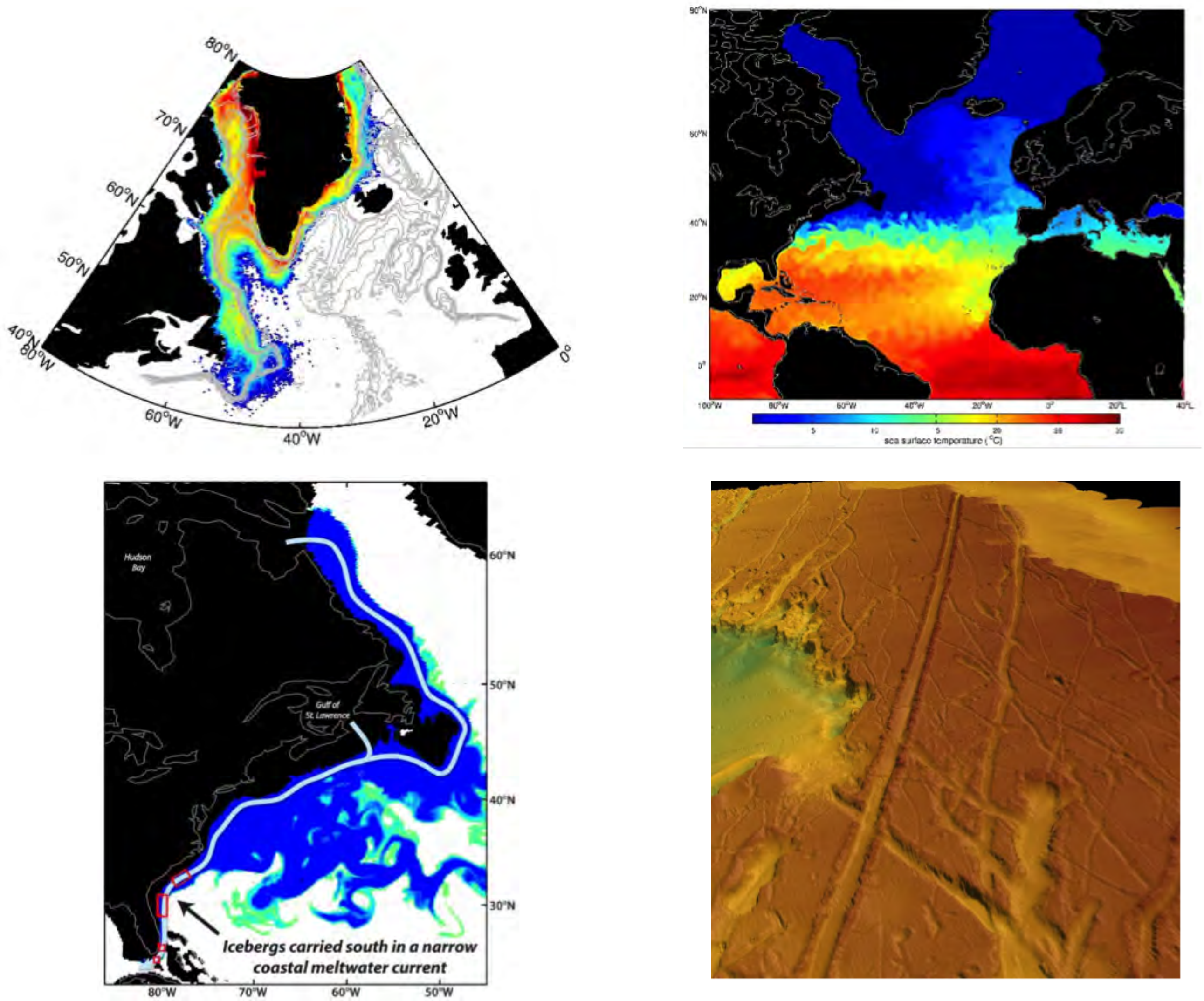

Figure 1: (top left) Towards realistic iceberg drift patterns in MITberg using a newly developed keel model. The colors show the average number of iceberg per grid cell every month. (top right) Development of a state-of-the-art, high resolution, glacial ocean-sea ice-iceberg model has provided a new level of insight into how the ocean circulated during colder glacial periods. (bottom left) Simulated transport route of iceberg-laden meltwater from Hudson Bay showing that large meltwater floods carried massive (up to 300 m thick) icebergs to Florida in the past. (bottom right) 3-D image of the sea floor showing one of several hundred iceberg scours found off the coast of Florida.

The Dynamics of Abyssal Mixing and Interior Transports Experiment (DynAMITE)

PIs: R. Curry and K. Polzin
Woods Hole Oceanographic Institution, Woods Hole, MA

This field program refined our knowledge of the structure and strength of the buoyancy gain part of AMOC – an Abyssal Upwelling Cell (AUC) that transforms the densest waters in the Atlantic (Antarctic Bottom Water, AABW, and Nordic Seas Overflow Waters) into warmer, lighter density classes (North Atlantic Deep Water, NADW) – and the circulation through the interior western basin that results. Conducted over a two-year time span, the DynAMITE field measurements included an array of moored profiling CTDs and current meters deployed down the southeast flank of Bermuda Rise and a microstructure/finescale survey to measure diapycnal mixing over the Mid Atlantic Ridge (MAR) and in the basins between the MAR and Bermuda.

In 2013/2014, processing and analysis of the 12-MMPs (moored profilers) and 18-VACMs (current meters) and MicroCats from the array were completed. These revealed the presence of a vigorous jet transporting an order 10 Sv of cold limb water masses (spanning depths 1500-4800 m) equatorward near the 4600 m isobath (Figure 1). Its volume transport is uncertain because the width of the jet was not resolved by the moorings: a nominal width of 60 km produces a mean equatorward transport of 10 Sv, while widths of 10 and 100 km yield mean transports of 2 and 18 Sv respectively. Our ideas about the structure, strength, and mechanisms driving this particular branch of the cold limb flows through the interior subtropical basin are based upon consideration of both historical observations and recent measurements.

Recent results

- A distinct interior flow feature conveys cold limb waters as a topographically steered current connecting the deep Gulf Stream in the vicinity of the New England Seamounts to the deep western boundary current (DWBC) south of Cape Hatteras via Bermuda Rise.
- The flows are appreciably strong, persistent in flow direction and location (tied to the 4500-5000 m isobaths), but the flow strength varies between quiescent and energetic periods on timescales of a few months.
- The mechanisms driving the mean transport may be related to alteration of the deep Gulf Stream's stratification (PV) where it runs into, over, and through the New England Seamounts.
- The temporal structure of the interior flows is subsequently modulated by the dynamics of planetary waves and/or mesoscale eddies interacting with the steep topography of Bermuda Rise.
- These persistent interior flows have consequences for the downstream AMOC variability through their contributions to DWBC volume transport and through alteration of PV distributions, stratification and water mass characteristics.
- The time scales for propagation of signals via this pathway may be considerably shorter than those associated with eddy-driven recirculation gyres, i.e., 5-10 years rather than decades.

Project website: http://www.whoi.edu/science/PO/dynamite/

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A Collaborative Multi-Model Study: Understanding AMOC Variability Mechanisms and Their Impacts on Decadal Prediction

PIs: G. Danabasoglu[1], S. Yeager[1], A. Karspeck[1], J. Tribbia[1], T. Delworth[2], R. Msadek[2], A. Rosati[2], Y.-O. Kwon[3], and C. Frankignoul[3]

[1] National Center for Atmospheric Research, Boulder, CO

[2] NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

[3] Woods Hole Oceanographic Institution, Woods Hole, MA

This collaborative project 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. Our specific goals include improving understanding of how particular physical processes and climate state information may give rise to predictive skill related to AMOC variability and evaluating how model differences in simulating AMOC variability affect related decadal predictability. During the first year of this proposal, work has begun towards accomplishing our goals. We summarize some of our recent progress below and note that several manuscripts are in preparation covering this work.

Recent results

Yeager and Danabasoglu (2014) have shown that buoyancy forcing over the Labrador Sea (LS) explains most of the decadal AMOC variability in a forced ocean–sea ice hindcast simulation. The simulation is forced with the Coordinated Ocean-ice Reference Experiments inter-annually varying atmospheric datasets, i.e., CORE-II. The study also shows that interannual buoyancy forcing perturbations, *not* wind forcing perturbations, explain most of the high latitude variations in barotropic circulation. Yeager (2014) investigates how topographic coupling between the large-scale overturning and gyre circulations explains buoyancy-driven gyre flow and momentum-driven overturning in similarly forced hindcast simulations. This analysis highlights the importance of abyssal flow interaction with spatially-varying bottom topography – quantified as the bottom pressure torque term (BPT) of the vertically-integrated vorticity balance – in determining both the mean large-scale Atlantic circulation as well as its response to surface forcing changes. For example, the hindcast simulation (CONTROL) exhibits large decadal variations in the high latitude AMOC, which are largely recovered in a sensitivity experiment (B) in which only buoyancy fluxes are allowed to vary interannually (Figure 1, panels a, f, and g). Composite differences between years of high and low buoyancy-driven AMOC show that there is a significant enhancement of cyclonic subpolar gyre circulation, as well as anti-cyclonic subtropical gyre circulation, in both CONTROL and B. In B, this gyre response can only be attributable to changes in BPT, because the experiment lacks any wind stress curl variability. Much, but not all, of the gyre response in CONTROL is also associated with this BPT effect. This highlights the profound importance of abyssal flow in understanding Atlantic circulation variability.

At WHOI, an analysis of AMOC both in depth and density coordinates has been completed. Specifically, Kwon and Frankignoul (2014) further explain the mechanism of the strong 20-year AMOC variability in the present-day control integration of the Community Climate System Model version 3 (CCSM3). The AMOC in density coordinate is shown to better represent the variability associated with the water mass transformation in the subpolar gyre, thus better correlated with the Atlantic meridional heat transport (AMHT) in the North Atlantic subpolar gyre (Figure 2). The figure shows that the density coordinate AMOC is closely correlated with AMHT at all latitudes without any lag, while the depth coordinate AMOC substantially leads AMHT in the subpolar gyre. Therefore, AMOC in density space reflects AMHT better at a given latitude, while AMOC in depth space may provide some predictive skill for AMHT. Further analysis for the relationship between the depth and density AMOC and AMHT from additional coupled climate simulations as well as the ocean-only simulations is on going.

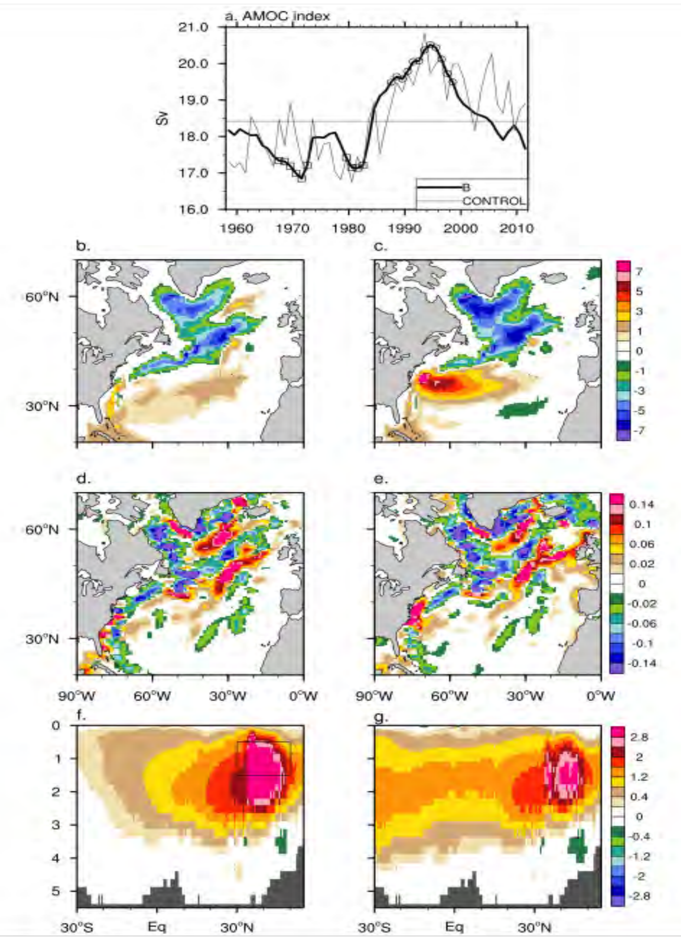

Figure 1. Atlantic circulation change associated with extremes in buoyancy-driven AMOC. Panel (a) shows the time series of high latitude AMOC strength (see box in panel f) from the CONTROL and B experiments of Yeager and Danabasoglu (2014). The remaining panels show multi-year composite differences (high-low) based on the ±1 standard deviation of the AMOC index from experiment B of: (b,c) barotropic streamfunction, (d,e) bottom pressure torque, and (f,g) AMOC streamfunction. Left panels are from experiment B and right panels are from CONTROL.

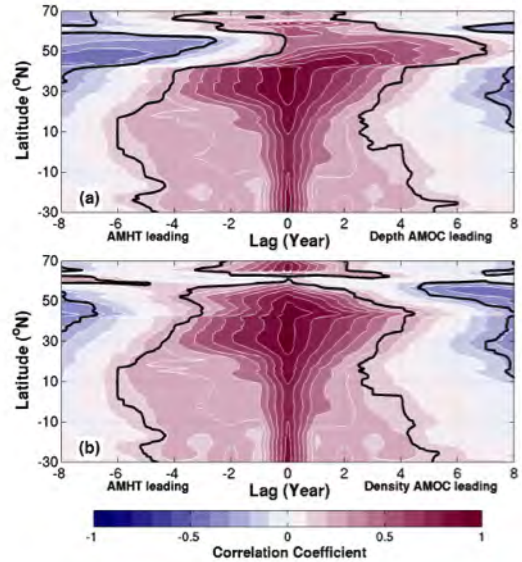

Figure 2. Lag-correlations between the maximum AMOC time series at each latitude and AMHT at the same latitude from years 150-399 of CCSM3 present-day control simulation. AMOC is calculated based on (top) depth coordinate and (bottom) density coordinate, respectively. Positive (negative) lags indicate AMOC leads (lags) AMHT at the same latitude. Contour interval is 0.1. Black contours indicate significance at 5% level.

At GFDL, diagnostic efforts exploring AMOC variability and the underlying mechanisms in a suite of coupled models have been continuing. Using multi-millennial pre-industrial simulations of three GFDL models (CM2.1, CM3, and FLOR), we investigate the robustness of the AMOC decadal variability characteristics. All models share similar oceanic resolution (~1°) and ocean mesoscale eddy parameterizations, but have differences in atmospheric resolution and physics. We find that the mechanism of AMOC variability in the three models is similar, but their timescales are different (periods of 20 years, 17 years, and 27 years for CM2.1, CM3, and FLOR, respectively; see Figure 3). In all three models the AMOC variability mechanism involves an increase of the LS convection in response to cooling induced by the winter positive North Atlantic Oscillation (NAO). This drives an AMOC acceleration over the subpolar region that propagates southward, which in turn yields an increased northward heat transport. At the same time, by geostrophic balance, the positive density anomalies over LS favor an acceleration of the subpolar gyre circulation, which leads to the creation of positive temperature anomalies over the subpolar gyre and LS regions, eventually contributing to a reversal phase of the oscillation. This study shows that models, which exhibit similar AMOC decadal mechanisms, can have different characteristic timescales. Because the skill in decadal predictions mainly comes from oceanic variations, the existence of these different timescales among the models can be particularly important: the predictable signal could be shifted up to 10 years following initialization. Further analyses are in progress to better understand the origin of this discrepancy.

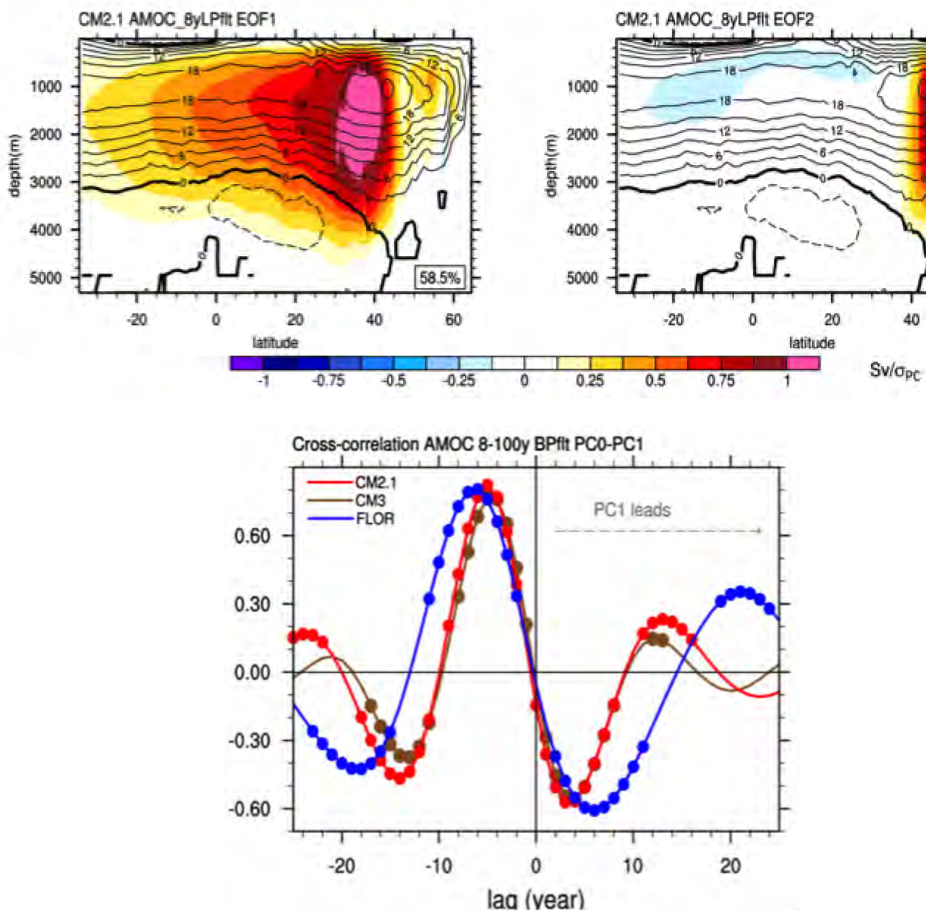

Figure 3. (top row) Solid contours show time-mean AMOC in the GFDL CM2.1 model, while color shading shows the amplitude of the first (left) and second (right) EOFs. The spatial patterns of the two leading EOFs from CM3 and FLOR are very similar and not shown. (bottom) Lagged correlations between the time series corresponding to EOF1 and EOF2 from the CM2.1, CM3, and FLOR models. The length of time between successive minima in the correlation functions indicates the dominant timescale of variability. The CM2.1 and CM3 models have similar correlation structures, indicating similar timescales of variability (~17-20 years). The different structure for the FLOR model indicates a longer timescale of variability (~27 years). However, for each model EOF2 leads EOF1 in time by roughly one-quarter of the dominant timescale of AMOC variability.

At NCAR, we have initiated an effort to compare the low-frequency AMOC estimates from a set of ocean reanalysis products – all of which were used for initialization of coupled model decadal predictions for the Coupled Model Inter-comparison Project phase 5 (CMIP5). The five reanalysis products that are included in the inter-comparison are ECDA3.2 (GFDL), ORAS4 (European Center for Medium Range Weather Forecasting), SODA 2.2.4 (U. of Maryland/Texas A&M), GECCO2 (U. Hamburg), and DePreSys (UK Met Office). Initial investigation of these ocean state reanalyses suggests that there is *no consensus* on the sign of the AMOC trend since the 1960's (Figure 4). In part, these differences can be understood through examination of the northward geostrophic shear flow induced by the zonal density differences across the Atlantic basin. While low frequency changes in the temperature and salinity in the upper 250 m of these analyses are in general agreement, below 250 m depth the analyses do not show consistent trends. Complimentary work at GFDL is focusing on the large spread among estimates of ocean heat content in these reanalysis products. This is particularly problematic considering that similar observations are used to constrain these systems. The heat content analysis emphasizes the impact of inhomogeneities of the observing system in time and space.

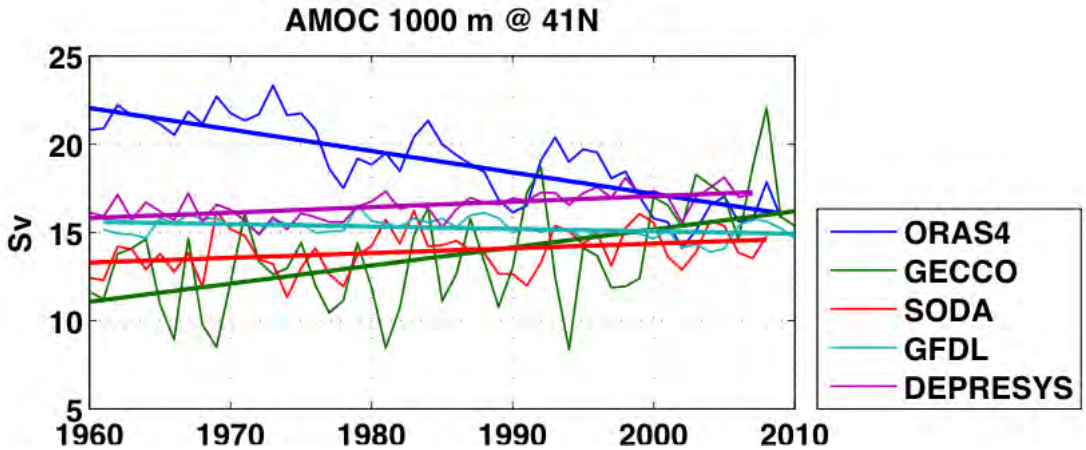

Figure 4. Historical AMOC at 41°N and 1000 m depth from five different ocean reanalysis products.

Another focus at GFDL has been on assessing the response of the AMOC and larger-scale climate to NAO-forcing. We have conducted suites of idealized NAO forcing experiments using GFDL CM2.1. For these experiments we define NAO forcing flux fields for heat, water, and momentum. The NAO-like fluxes are applied to the ocean component of the coupled model at each time step, in addition to the fluxes calculated from ocean-atmosphere differences. Differences between an ensemble of simulations with the NAO forcing and a control simulation are then taken as an estimate of the climatic impact of NAO variations. We have conducted multiple ensembles using various temporal scales and amplitudes of the anomalous NAO forcing, and with various combinations of the flux forcing terms (heat, water, and stress). We show that an arbitrary switch on of the NAO forcing is able to excite AMOC variations that resemble the model's natural mode of AMOC variability. We also show that the AMOC response is sensitive to the time scale of NAO forcing, with substantial responses only for timescales comparable to or longer than the dominant mode of internal AMOC variability of the model. The NAO-induced AMOC changes are subsequently able to generate a hemispheric scale response in surface air temperature. There is large-scale warming (cooling) in response to a positive (negative) NAO induced strengthening (weakening) of the AMOC. The temperature response is larger for low-frequency NAO variations. Using realistic temporal variations of the NAO over the 1951-2013 period, we show that NAO-induced changes in the AMOC may have contributed significantly to hemispheric cooling in the late 1960s through early 1980s, although there is some model-dependence of the results. Our plan is to conduct similar NAO impact experiments with the Community Earth System Model (CESM) at NCAR.

Finally, GFDL and NCAR have started design and coordination of a suite of joint experiments to study impacts of the Atlantic Multidecadal Variability (AMV) on climate, particularly in terms of weather regimes. The set of initial experiments involves imposing sea surface temperature (SST) anomalies associated with AMV in the Atlantic basin – either idealized or historical SST patterns.

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Collaborative Research EaSM2: Mechanisms, Predictability, Prediction, and Regional and Societal Impacts of Decadal Climate Variability

PIs: G. Danabasoglu[1], J. L. Anderson[1], G. Branstator[1], K. Lindsay[1], J. Tribbia[1], C. Frankignoul[2], Y.-O. Kwon[2], and M. Zhang[3]
Collaborators: S. G. Yeager[1], A. Karspeck[1], M. C. Long[1], L. Jiang[1], and H. Teng[1]
[1] National Center for Atmospheric Research, Boulder, CO
[2] Woods Hole Oceanographic Institution, Woods Hole, MA
[3] Stony Brook University, Stony Brook, NY

The goals of this interdisciplinary collaborative project are: i) to produce an improved and reliable decadal prediction system within the Community Earth System Model (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. In order to achieve these overarching goals, we are engaged in advancing our understanding and technical capabilities in four fundamental areas related to decadal prediction: (1) improving our understanding of intrinsic decadal variability and mechanisms; (2) evaluating the inherent predictability constraints of our forecast model; (3) evaluating practical forecast system design methods; and (4) generating capabilities for incorporating fully-coupled data assimilation and ocean ecosystems and biogeochemistry into our decadal prediction system. We summarize some of our recent progress below and note that several manuscripts are in preparation covering this work.

Recent results

We have investigated the robust and non-robust aspects of the Atlantic Meridional Overturning Circulation (AMOC) variability in the fully-coupled CESM by comparing long (at least 600-year) simulations which differ only in their atmospheric initial conditions, in their atmospheric model resolution, or in their settings for a few loosely-constrained parameters used in various sub-gridscale physics parameterizations in the ocean model. The latter set includes experiments in which parameters in mesoscale and submesoscale mixing of tracers, horizontal viscosity, and vertical mixing are changed in the ocean model. The initial condition and physics perturbation experiments are branched from and compared to a 1500-year pre-industrial coupled control simulation (LE) which uses a version of CESM with nominal 1° configurations of the component models and with the finite volume dynamical core Community Atmospheric Model version 5 (CAM5). We have also analyzed a long control simulation of the last millennium, which uses the 2° configuration of the atmosphere coupled to the 1° ocean model. The power spectra of the AMOC indices obtained in this suite of runs shows a surprising variety of significant spectral peaks (Figure 1). The roughly ~100-year period AMOC variance seen in LE is not replicated in any of the perturbation experiments, which show different concentrations of spectral power at timescales between 10-100 years. Even the simulations, which differ from LE only in terms of a round-off level perturbation to their atmospheric initial conditions (cases 005, 008, and 009), show AMOC spectra, which are distinct from LE. A clear implication is that (600-year) control simulations are much too short to assume that AMOC variability can be described by stationary statistics.

However, more in-depth analysis of this suite of experiments has revealed several aspects of AMOC variability that appear to be quite robust in the CESM framework. In all of the simulations shown in Figure 1, large increases in AMOC are preceded by an enhancement of the Labrador Sea (LS) upper ocean density and deep convection, which are related to positive North Atlantic Oscillation (NAO+) conditions in the atmosphere (Figure 2). The spin up of AMOC is coincident with a strengthened (cyclonic) subpolar gyre transport. The analysis implies that the inverse is also true, i.e., AMOC weakening is preceded by NAO- and reduced deep convection in LS. However, further work is needed to clearly separate the mechanisms associated with AMOC strengthening and weakening, and to explore the extent to which the mechanism is a function of the magnitude of AMOC anomalies.

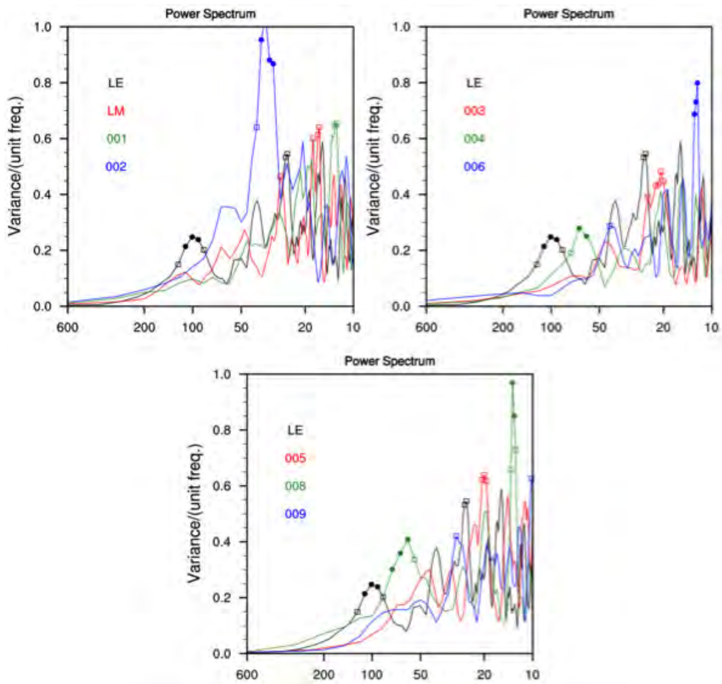

Figure 1. Power spectra of AMOC from the CESM pre-industrial (LE) and last millennium (LM) control simulations along with perturbation experiments which differ from LE in terms of parameterized physics settings in the ocean model (cases 001, 002, 003, 004, and 006) or atmospheric initial conditions (cases 005, 008, and 009). Maximum transport at 45°N subject to a 10-year low-pass filter is used as the AMOC index.

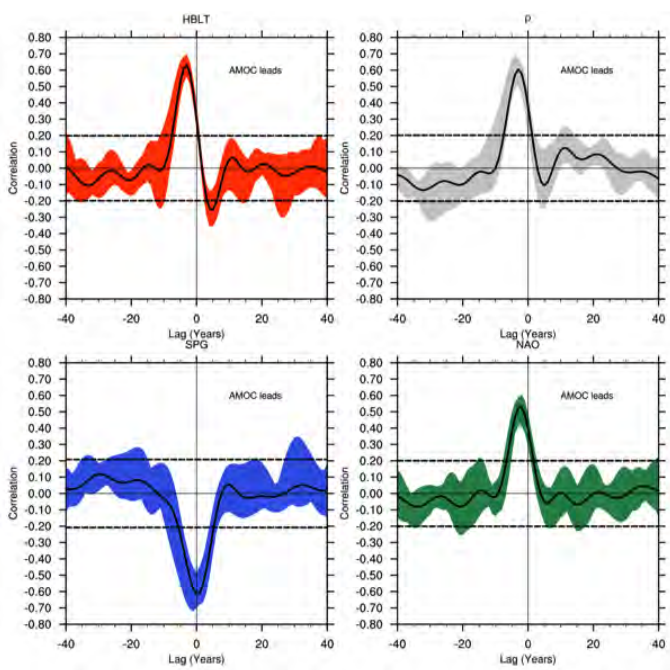

Figure 2. AMOC index correlations with (top left) March-mean boundary layer depth averaged over LS; (top right) upper ocean density averaged over LS; (bottom left) subpolar gyre barotropic transport; and (bottom right) a winter NAO index. The thick black lines give the mean correlation (averaged over all experiments shown in Figure 1), and the shading gives the correlation spread. Maximum transport at 45°N is used as the AMOC index. All time series use a 10-year low-pass filter.

We have recently made considerable progress in understanding the mechanisms at work in CESM decadal prediction simulations carried out following the Coupled Model Inter-comparison Project phase 5 (CMIP5) protocol. Our previous analyses of the CESM decadal prediction ensemble simulations looked at forecasts initialized every five years from 1961-2006, but we have now completed a set of predictions initialized every January 1st between 1955-2014. The ocean and sea ice initial conditions are obtained from a forced ocean–sea ice hindcast simulation. The new set of decadal prediction ensembles has allowed us to further elucidate the fundamental physical processes, which underpin the significant skill in predicting sea surface temperature (SST) anomalies in the subpolar North Atlantic. We find that there is very little skill in predicting the water mass formation processes which determine the upper 1000 m density anomalies in LS (Figure 3, left panel), but extremely high skill in predicting the propagation of pre-formed LS water mass anomalies into the Grand Banks shelf region (Figure 3, right panel). The latter is associated with key large-scale Atlantic circulation anomalies that govern the oceanic heat transport into the subpolar North Atlantic, resulting in high prediction skill for subpolar gyre SST and North Atlantic sector sea ice extent.

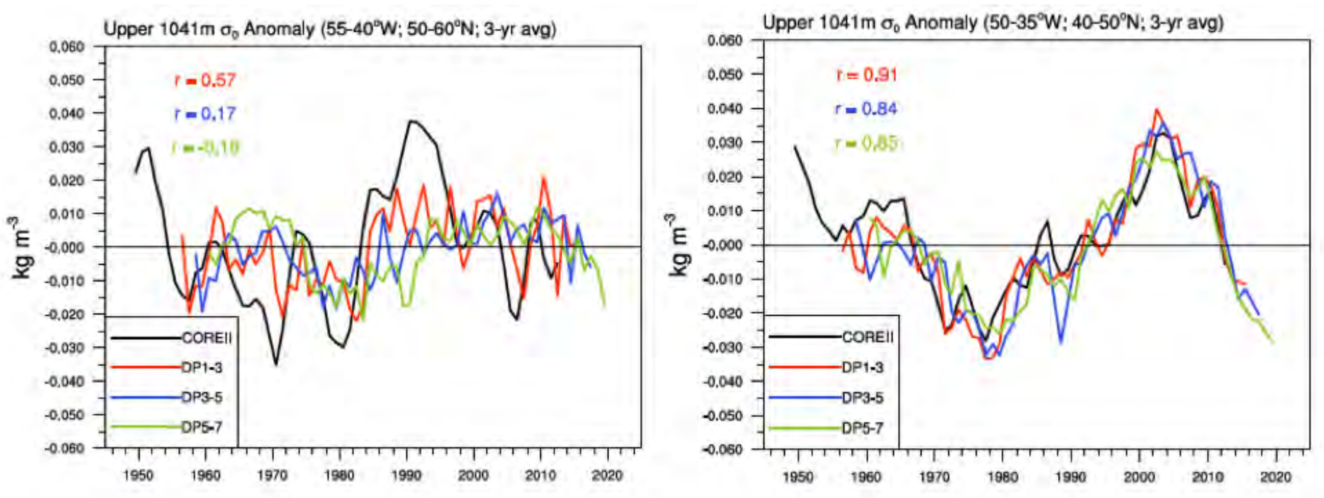

Figure 3. Upper 1000 m density anomaly in a LS box region (left) from the forced ocean–sea ice hindcast experiment used to initialize the CESM decadal prediction ensembles, and from the decadal prediction ensemble-mean averaged over lead times of 1-3, 3-5, and 5-7 years; (right) same as left panel but averaged over a Grand Banks shelf region.

We have expanded our analysis of the feedbacks between AMOC variability and atmospheric circulation, using a 1300 year-long pre-industrial control simulation of the Community Climate System Model version 4 (CCSM4). This analysis employs a lagged maximum covariance analysis. The feedback is the strongest in winter. Positive phase of the winter NAO is found to precede an AMOC intensification by a few years, while the negative NAO-like atmospheric circulation anomalies appear following the AMOC intensification by about seven years. The negative NAO-like atmospheric response is driven by a meridional SST dipole with warming in the subpolar gyre and cooling near the Gulf Stream (GS)-North Atlantic Current (NAC). The meridional SST dipole alters the low-level baroclinicity near the storm track by shifting the maximum eddy growth southward. The SST anomalies originate from a deep circulation change. Stronger AMOC is associated with the stronger deep equatorward flow, which interacts with surface currents to result in an equatorward shift of the GS-NAC path near the tail of Grand Banks and also a poleward shift downstream near the Mid-Atlantic Ridge (Figure 4). A zonal SST dipole caused by the GS-NAC path shifts in the opposite directions subsequently becomes a meridional SST dipole. The result is a perturbation of the atmospheric storm track, as the downstream warm anomalies advect cyclonically in the subpolar gyre. This process explains the seven year lag between the maximum AMOC anomaly and the atmospheric response.

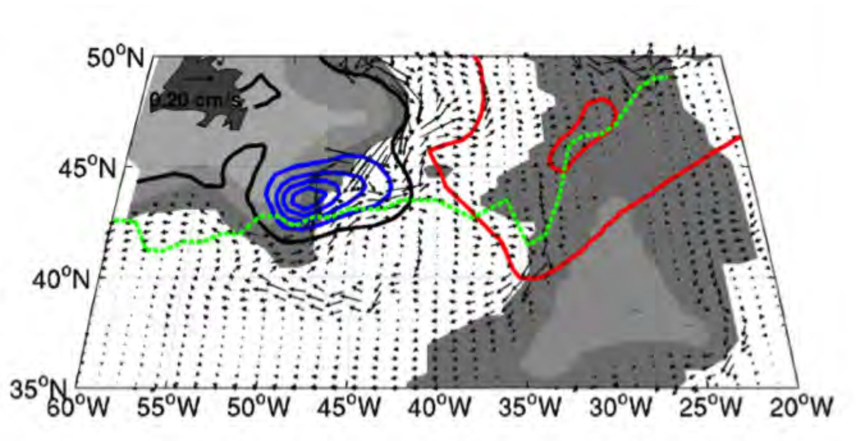

Figure 4. Regressions of SST (contours) and 2000-3000 m velocity (vectors) on the AMOC first principal component in CCSM4 pre-industrial control integration. Red/blue/black contours indicate positive/negative/zero SST anomalies, respectively. Contour interval is 0.1°C. Green dashed line indicates the mean GS-NAC position. Gray shadings from light to dark indicate 500, 2500, and 4000 m isobaths, respectively.

We have continued our investigation of the decadal variability of the number and intensity of winter cyclones in the Northwestern Atlantic and the US Northeast coast by analyzing model data from the CMIP5 archive. Our domain of interest is bounded by 20°-60°N and 40°-90°W. To identify cyclones, we have used the following criteria: i) a closed contour of sea level pressure with a minimum of at least 2 hPa less than the value of the closed isobar; and ii) events that last at least 24 hours and travel longer than 1000 km. For the cool season from November 1 to March31 , there is an average of about 105 cyclones in each year for the 1979-2004 period. We find that from 1980 to 1992, there is an increasing trend of wintertime cyclones; while from 1992 to 2004, the number of cyclones decreases. The time series of the number of coastal cyclones in the US Northeast is shown as the solid blue line in Figure 5. Simulated cyclones in the CMIP5 models during this period, including that from CESM, are also shown in the figure. We find that the majority of the models underestimate the number of cyclones. The models also fail to capture the inter-decadal variability. Work is ongoing to use the Weather Research and Forecasting (WRF) model with observed SST and the CESM large-scale atmospheric fields as lateral boundary conditions to study whether the inter-decadal variation of the number of winter cyclones can be simulated in WRF.

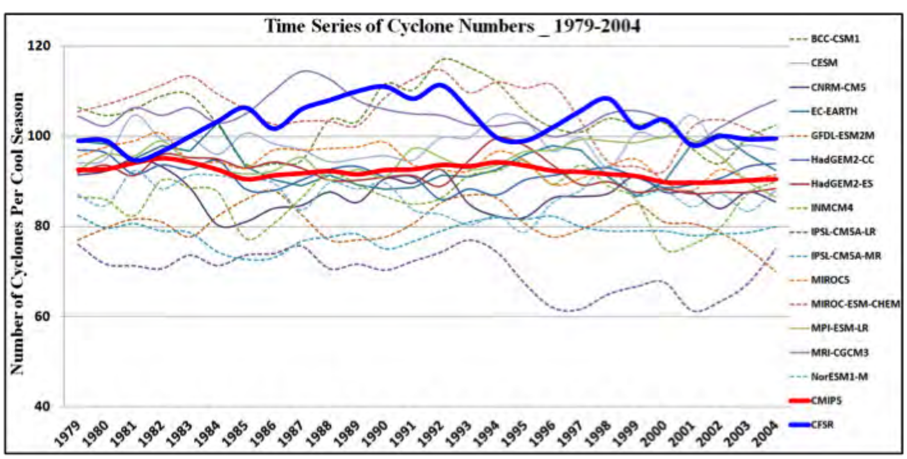

Figure 5. Inter-decadal variation of the number of wintertime (November to March) coastal cyclones in the US Northeast in reanalysis (CFSR, solid blue line), and in CMIP5 models (solid red line is the ensemble mean).

Finally, in collaboration with X. J. Davis and T. M. Joyce (both of Woods Hole Oceanographic Institution), we have investigated potential predictability of the GS latitude and its implications for the prediction of fish distribution in the US Northeast shelf. The position of the 15°C isotherm at 200 m depth is a well-known indicator of the GS path. An index of GS latitude is calculated beginning in 1954 with seasonal resolution based on the historical temperature measurements. Over the past ~40 years, the distribution of silver hake on the US Northeast shelf is found to be closely related to changes in the GS latitude. The correlation coefficient between the fall GS position and the center of biomass (COB) of spring silver hake reaches as high as 0.75 when the GS leads the silver hake by 0.5 years. Based on this lead-lag relationship and low-frequency variability of GS position with a dominant period of ~9-10 years over the past ~50 years, the GS path index is used as a predictor for the COB of silver hake in a linear autoregressive (AR) model. As the first step, fall GS position is predicted out to five years using a 5th order AR model and the observed GS position in preceding years. Then, the predicted GS position is used to further predict the COB of silver hake in subsequent spring based on their observed lagged linear relationship (Figure 6). Three different AR models are compared for the SH prediction. The predicted SH time series can explain as much as 69% of the variance of the observations for the first year prediction and 41 % for the fifth year prediction. Our results indicate that the predictions including GS as a predictor produce better prediction skills of silver hake COB than the AR model prediction solely based on the observed silver hake time series. We plan to extend this study to include relationships with AMOC variability.

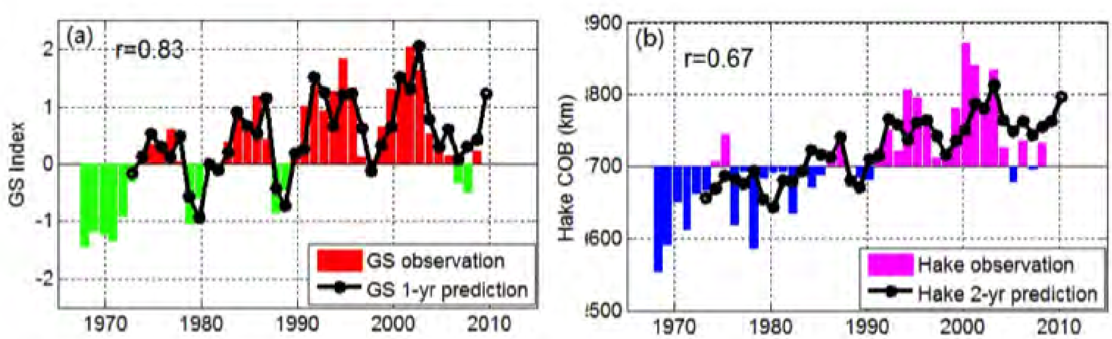

Figure 6. (a) Observed (color bars) and statistically predicted (black curve) fall GS path latitude. Each prediction is made based on the previous five data points and 5th order linear AR model. The correlation between the observed and predicted time series is 0.83. (b) Observed (color bars) and statistically predicted (black curve) spring silver hake distribution on the US Northeast shelf. The silver hake prediction is based on the GS prediction and the linear lag-regression between the observed GS and silver hake. The correlation between the observed and predicted time series is 0.67.

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Pathways to the Denmark Strait Overflow: A Lagrangian Study in the Iceland Sea

PIs: M. F. de Jong[1], H. Soiland[2] and A. S. Bower[1]
[1]Woods Hole Oceanographic Institution, Woods Hole, MA
[2]Institute of Marine Research, Bergen, Norway

About half of the overflow water entering the North Atlantic Ocean from the Nordic Seas originates from the Denmark Strait overflow. The Denmark Strait overflow water is also the densest component of North Atlantic deep water. It was previously thought that the dense water upstream of the overflow originated from Atlantic water that was modified along its path through the Nordic (and Arctic) Seas (Mauritzen 1996) finally being transported to Denmark Strait in the East Greenland Current. More recent observations suggest that there may be an alternative source in the Iceland Sea, with a pathway to the Strait along the northern shelf of Iceland in the North Icelandic Jet (Våge et al. 2011), and a complicated circulation in the narrow region just upstream of Denmark Strait (Våge et al. 2013). Model studies (Köhl et al.; 2007; Köhl 2010) suggest that both pathways may be a source and alternate depending on the wind forcing around Iceland. This has potential implications for the stability of the Denmark Strait overflow under future atmospheric conditions.

This project aims to elucidate the circulation upstream of the Denmark Strait sill. In July 2013 a total of 26 floats (13 one-year floats and 13 two-year floats) from the Institute of Marine Research (IMR) in Bergen, Norway were deployed in the Iceland Sea, along with six sound sources. The RAFOS deployments were spread out over the interior Iceland Sea and the Greenland and Iceland slopes. Another PI at IMR deployed two profiling Argo floats, and the data will be made publically available. In May 2014, 11 of the scheduled 13 floats surfaced, two appear to be lost. An additional 26 floats (20 from WHOI and six from IMR) were deployed in July 2014. The deployment plan was based on the data available from the surfaced floats and focused more on the slopes and less on the interior basin, where several floats are still expected to reside. One seeming malfunctioning sound source was replaced and another Argo float was deployed. At this point, all the fieldwork associated with the project is done.

The second part of the project consists of a model collaboration with Armin Köhl at the University of Hamburg. The high resolution (1/12°) model run used for the study described by Köhl 2010 will be extended to the end of the experimental part of this project, using the atmospheric forcing that was observed during this period. This will allow us to compare the model and the float trajectories and to assess the interannual variability.

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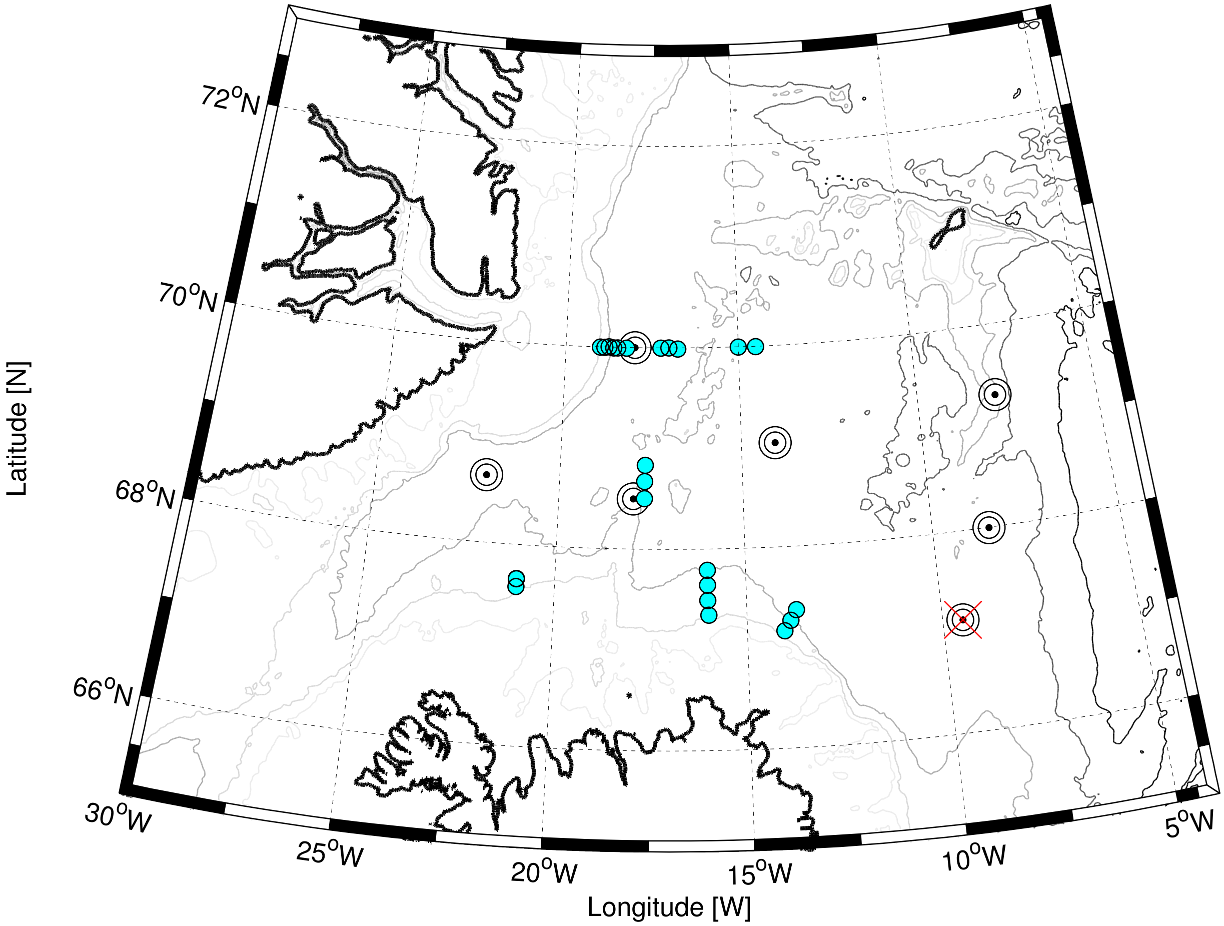

Figure 1. Positions of RAFOS floats deployed in 2014. On this cruise, one sound source (marked with a red x) was recovered and a new sound source was deployed off the east Greenland shelf at 70°N. Floats are ballasted for the 500m isobaths, below the 28 kg/m^3 isopycnal and above sill depth.

The Oleander Project: Sustained Observations of Ocean Currents in the NW Atlantic Between New York and Bermuda

PIs: K. Donohue[1], C. Flagg[2], and T. Rossby[1]
[1]University of Rhode Island, Narragansett, RI
[2]Stony Brook University, Stony Brook, NY

Since late 1992, high-horizontal resolution upper-ocean velocity has been sampled by an acoustic Doppler current profiler (ADCP) mounted in the hull of the container vessel CMV Oleander, which operates on a weekly schedule between New Jersey and Bermuda. In addition to velocity, the Oleander Project includes monthly expendable bathythermograph (XBT) sections. The XBT and thermosalinograph (TSG) program are no longer maintained by the National Marine Fisheries Service. The Oleander Program has taken over that responsibility. We continue to deliver data via the Oleander website (links below) and have included several downloadable files of Gulf Stream North Wall position and upper ocean fluxes along the Oleander line.

Our goal is to provide a framework for the development and testing of new concepts afforded by the systematic and sustained measurements of ocean currents across four distinct regions: the continental shelf, slope sea, Gulf Stream, and northwestern Sargasso Sea. Specifically, our objectives include 1) to continue the Oleander velocity program to elucidate long-term climatological variability; 2) to enhance the existing program with an expanded XBT temperature measurement program; 3) to provide near-real-time processed data distribution to enable broad community participation in scientific analysis; and 4) to investigate the linkages between these oceanographic regimes and their connections to large-scale forcing fields.

Recent results

The Oleander dataset shows no evidence of a decrease in Gulf Stream transport -- in contrast to recent claims of a Gulf Stream slow-down (Rossby et al. 2014; Figure 1). The Oleander ADCP measurements allow us to define a well-constrained definition of Gulf Stream width. The linear least square fit to surface layer Gulf Stream flux yields a 0.13% negative trend per year. Assuming geostrophy, this corresponds to a sea level decrease of 0.03 m over the 20-year period. But, these estimates are not significantly different from zero at the 95% confidence level.

A combination of *in situ* and satellite measurements were used to track various different proxies of Gulf Stream position (Sanchez-Franks et al. 2015). Local measures of Gulf Stream path are then compared with a meridionally averaged Gulf Stream position index to verify that the estimates are internally consistent. Gulf Stream transport and position are also compared to Florida Current transport. Results indicate the Florida Current does not have a detectable signal in the Gulf Stream east of Cape Hatteras.

Online data

ADCP: http://po.msrc.sunysb.edu/Oleander/
TSG: http://po.msrc.sunysb.edu/Oleander/TSG/TSG.html
XBT: http://po.msrc.sunysb.edu/Oleander/TSG/TSG.html
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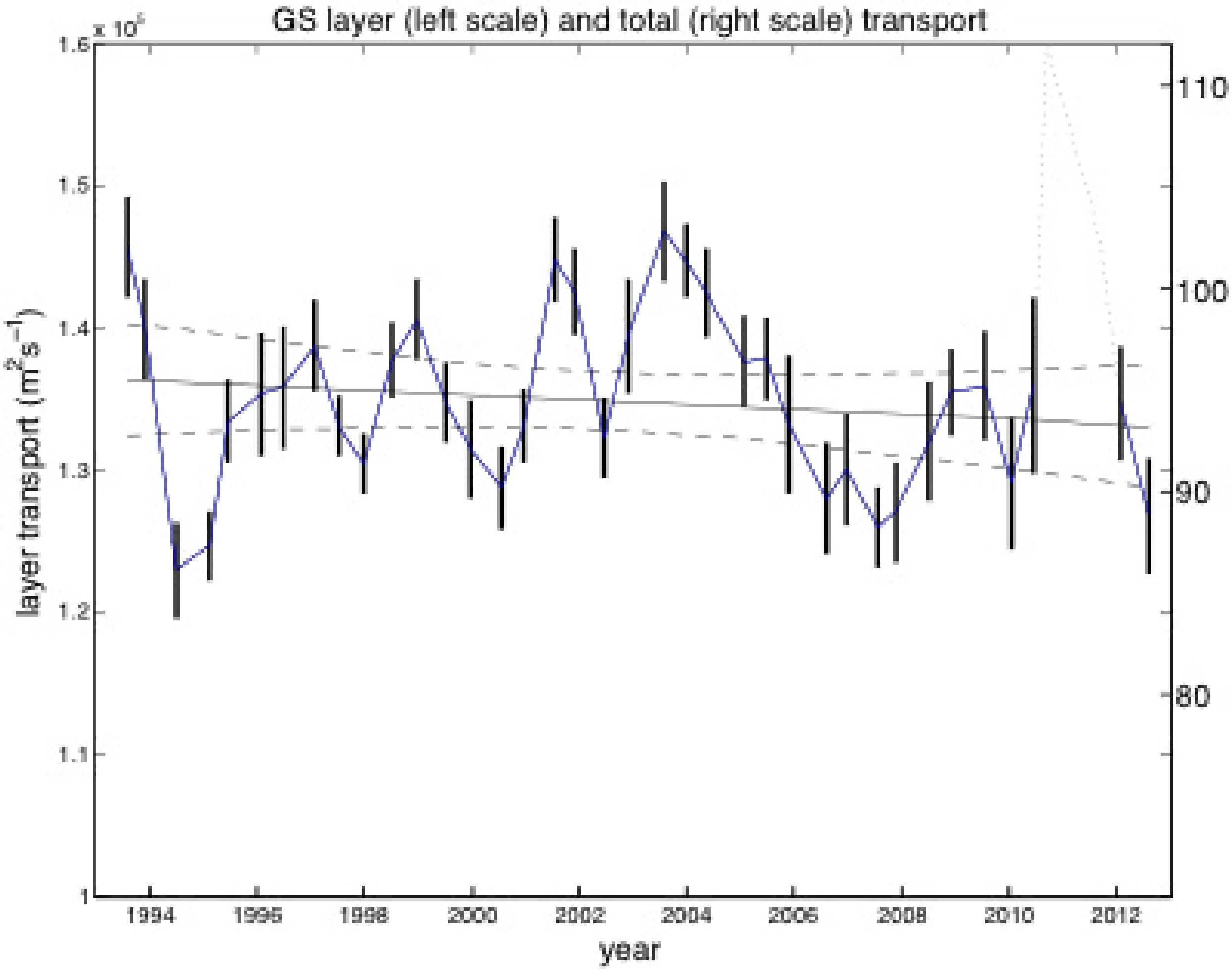

Figure 1. Annually averaged Gulf Stream surface layer flux (termed `layer transport') stepped every half-year. The mean = (1.34 ± 0.6) x 10^5 m^2s^{-1}. The slope of the line = -173±377 $m^2s^{-1}yr^{-1}$, equivalent to a decrease in sea level difference of 1.5±3.3 mm yr^{-1} or 0.03 m over the 20-year observing period. The dashed lines indicate the 95% confidence limits of the linear fit. 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 dotted line in 2011 reflects a scarcity of data due to an extended dry dock period and instrument difficulties after the dry dock period. The Gulf Stream is the region of flow parallel to the maximum velocity vector between the zero crossings on either side of the maximum. Figure from Rossby et al. 2014.

A Generalized Stability Analysis of the AMOC in Earth System Models: Implication for Decadal Variability and Abrupt Climate Change

PI: A. Fedorov[1],
International Collaborators: F. Sevellec[2]
[1]Yale University, New Haven, CT
[2]National Oceanography Centre, Southampton, U.K.

The central goal of this project is to study the mechanisms that control the stability of the Atlantic Meridional Overturning Circulation (AMOC), including the mechanisms of abrupt climate change and its predictability, by means of a generalized stability analysis. An additional inherent component of the project is to evaluate AMOC variability and its climate impacts in the Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset.

Recent results

Over the past year we have investigated how variations of the AMOC affect sea surface temperature (SST) within the simulations of CMIP5 (Muir and Fedorov 2014). In particular, we explore whether the SST response is interhemispheric in nature, specifically as reflected in the Atlantic SST dipole index, or whether the response is localized more in the North Atlantic Ocean. In the absence of direct observational data, this dipole index has been proposed to approximate AMOC variations over the duration of the instrumental temperature record.

We find that typically, on timescales between decadal and centennial, the SST dipole index correlates with the AMOC with coefficients ranging from 0.2 to 0.7, typically with a 0 to 6 year lag, and thus explains less than half of the AMOC variance. In just two models this value slightly exceeds 50%. Even for the models with the highest correspondence between the AMOC and the dipole index, the correlation between the two variables is controlled mainly by SST variations in the North Atlantic, not the South Atlantic, both for the model control and historical simulations. While the relationship between the AMOC and the North Atlantic SST is largely consistent across the models, the relationship of the AMOC and the South Hemisphere Atlantic SSTs temperatures shows little to no consistency, as seen for example from SST regression maps (Figure 1). Consequently, in nearly all models, the North Atlantic SST provides a better indicator of AMOC variations than the Atlantic dipole. Thus, on decadal to centennial timescales, AMOC variability affects mainly the North Atlantic Ocean, with the sensitivity of the North Atlantic SST between 40-60°N, given by the multi-model average, of about 0.3˚C per 1 Sv of AMOC change, explaining roughly one third of the SST variance.

We discuss our results in the context of the connection between the AMOC and the Atlantic multidecadal variability (AMV). On one hand, our results support the notion that a significant albeit not too large a fraction of the AMV should be related to AMOC variations. In fact, we find that the region of the maximum SST response to AMOC simulated by the models, south of Iceland and Greenland and east of Canada, generally coincides with the region of the strongest AMV signal in the observations. However, finding a robust SST response of the Southern Atlantic to AMOC variation in the north on decadal to centennial timescales was not successful.

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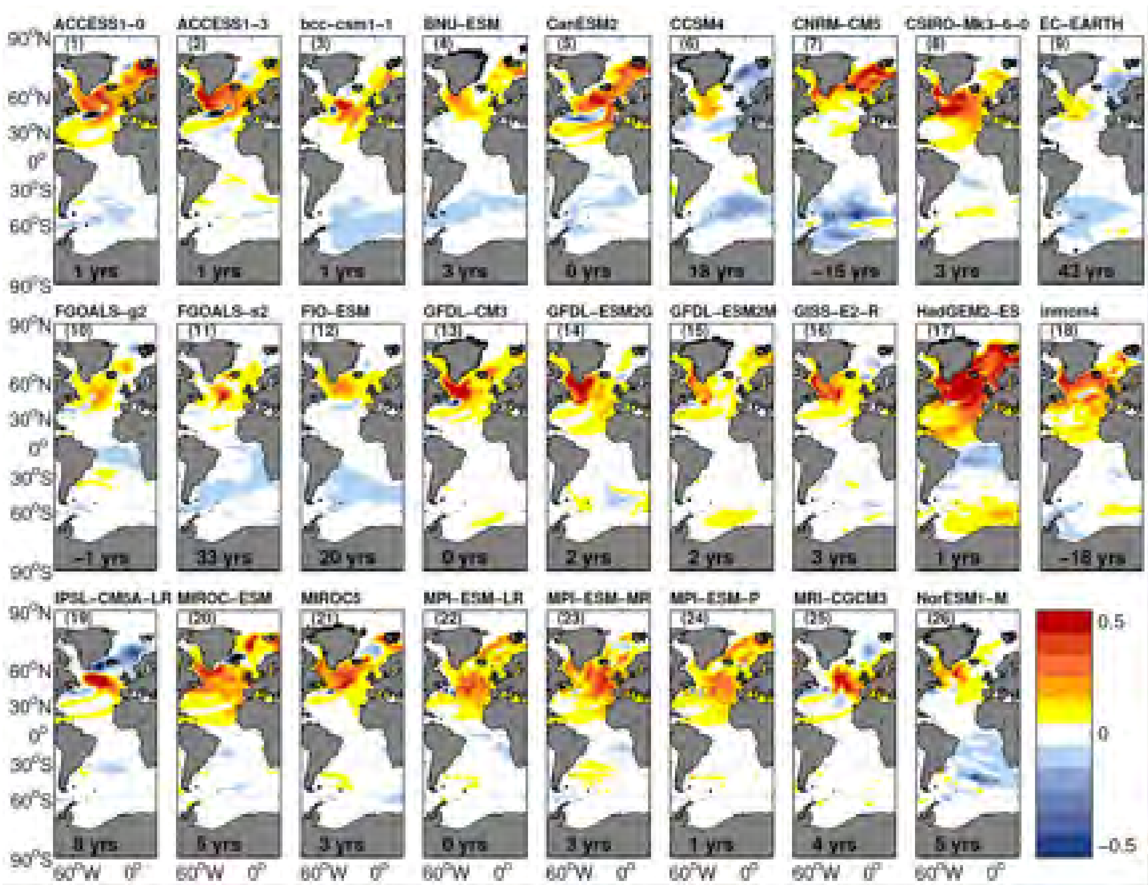

Figure 1. Regressions of SST onto the AMOC index (evaluated at 30˚N) at the lag corresponding to the maximum correlation between the AMOC and the Atlantic dipole (the best lag). SST changes (in ˚C) for a 1 Sv increase in the AMOC are shown. Numbers at the top of each panel indicate the models number; numbers at the bottom of the panels indicate the lag (in years) of the dipole index with respect to AMOC variations. The maximum SST response is found in the northern Atlantic, typically between 40°N and 60°N. The Southern Atlantic exhibits no or very week signal.

Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt

PIs: S. Gille[1] and D. Martinson[2]
[1]University of California, San Diego, CA
[2]Lamont-Doherty Earth Observatory, Palisades, NY

Our project focused on assessing meridional heat transport towards the Antarctic continent. As in past years, we have continued to focus on the Pacific Meridional Overturning Circulation, because of its sensitivity to El Niño forcing, and because the most rapid melting of the Antarctic continent has been reported in the southeastern Pacific sector of Antarctica. The advent of high-quality Argo trajectory data now provides usable reference velocity information, which has opened new avenues for assessing meridional overturning. These data, together with data from the Palmer Antarctic Long-Time Ecological Record (LTER), have provided us with a broad perspective on meridional overturning circulation in the South Pacific Ocean and have extended our analysis to consider a broad range of contributors to the meridional overturning circulation.

Recent results

Argo float trajectories significantly influence our estimates of meridional transport at 32°S in the Pacific Ocean. We see evidence for enhanced meridional transport along the western flank of the East Pacific Rise. Overall this enhanced topographically driven transport gives us a refined estimate of the net meridional transport in the South Pacific (Zilberman et al. 2014) and suggests a significant modification to the meridional overturning in the ocean interior that would be inferred from a constant depth reference velocity (Zilberman et al, in preparation). At 32°S, meridional transport in the western boundary current is correlated with the Southern Annular Mode (SAM), but not with changes in El Niño and Southern Oscillation (ENSO), as measured by the Niño 3.4 index. In contrast, at latitudes north and south of 32°S, we see a stronger link to ENSO, implying regional modulations to the meridional transport. Figure 1 shows that under high SAM conditions, the wind-stress curl varies substantially along the western boundary of the Pacific basin, resulting in spatially varying patterns of variability.

The frontal jets that comprise the Antarctic Circumpolar Current (ACC) are often hypothesized to vary in response to the wind, and in previous studies, satellite altimeter data have been used to infer a large-scale poleward shift in the position of the ACC frontal features in response to a large-scale poleward shift in winds over the Southern Ocean, associated with an intensification of the SAM. For this study, we used altimeter data to define an index of the mean latitude of water transported by the ACC. In contrast with the sea surface height trends, the transport-latitude index indicates no long-term trend, implying a possibility that the long-term trends in sea surface height are indicative of steric expansion of the ocean and not of a poleward shift in geostrophic jets (Gille 2014).

Analyses of hydrographic data near West Antarctica indicate that Upper Circumpolar Deep Water (UCDW) is warming in parallel with the Southern Ocean as a whole. This suggests that UCDW warming originates in the Southern Ocean, and may reach the Antarctic margin as an eddy driven transport. This water is a response to oceanic processes and local wind-stress curl, rather than being a response to atmospheric warming. Data from the LTER and a six-year analysis based on the Southern Ocean State Estimate both underscore the importance of locally-forced input to the shelf (Martinson and McKee 2012; Gilroy et al, in preparation).

Work by K. Drushka examined upper-ocean processes in the equatorial Indian Ocean (Drushka et al. 2014a) and the diurnal cycle in salinity (2014b), showing substantial variability in the upper ocean. We are now transferring this understanding of mixed-layer processes to an analysis of the Southern Ocean to look at ocean heat uptake and its impact on overturning circulation.

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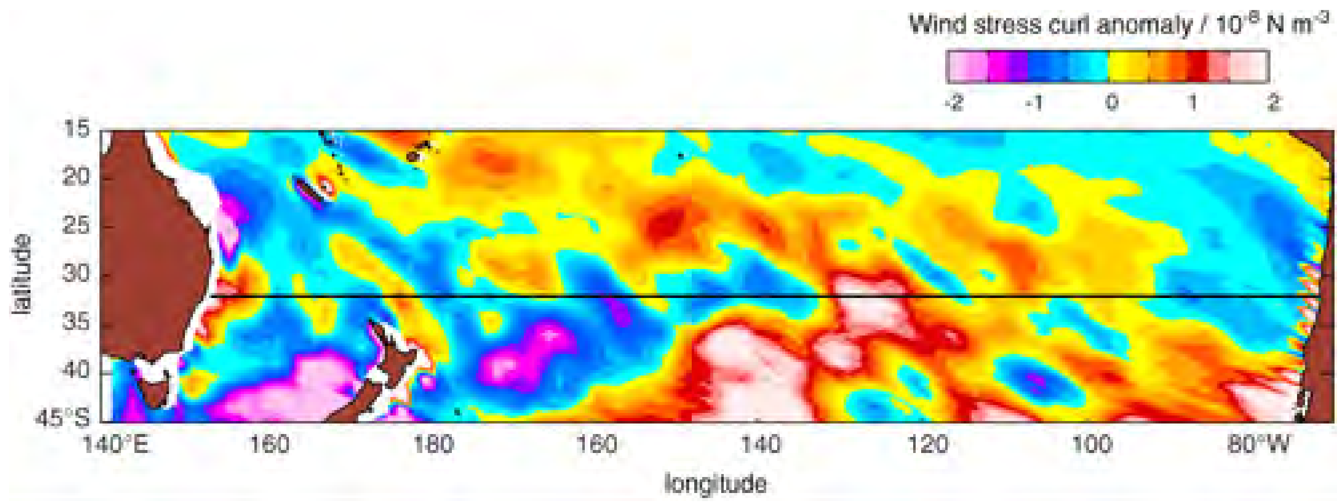

Figure 1. Wind stress curl anomaly averaged over times when the SAM index is greater than 0.25, during 2004–2012. The black line indicates 32°S.

Meridional Variability of the South Atlantic Meridional Overturning Circulation

PIs: G. Goni[1] and S. Dong[1,2]
[1] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
[2] University of Miami, Miami, FL

Satellite altimetry measurements are used to investigate the spatial and temporal variability of the Meridional Overturning Circulation (MOC) and Meridional Heat Transport (MHT) in the South Atlantic. Synthetic temperature and salinity profiles are derived from altimeter sea surface height anomaly (SSHA) along zonal sections between 20°S and 34.5°S where SSHA and isotherm depths are highly correlated. Our estimates of MOC/MHT from those synthetic temperature/salinity profiles compare well with previous estimates from expendable bathythermograph (XBT) measurements. Consistent with studies from XBTs and Argo data, both the geostrophic and Ekman contributions to the MOC exhibit strong annual cycles, and play an equal role in the MOC seasonal variations. The strongest variations on seasonal and interannual time scales in our study region are found at 34.5°S. The dominance of the geostrophic and Ekman components on the interannual variations in the MOC varies with time and latitudes.

The Upstream Sources of the Denmark Strait Overflow

PIs: B. E. Harden and R. S. Pickart
Woods Hole Oceanographic Institution, Woods Hole, MA

The aims of this project are to quantify the upstream sources of the Denmark Strait Overflow Water (DSOW) and relate the variability in the different sources to that observed at the sill. To accomplish this we are using time series data provided by four institutions, who together deployed 12 moorings spanning the strait 200 km north of the sill from Aug 2011 – Aug 2012, plus a mooring at the sill itself. The first objective is to quantify a newly discovered pathway of dense water in the central portion of the strait, known as the separated East Greenland Current (sEGC). This pathway was recently revealed in a number of shipboard crossings and is thought to be a free-jet located between the boundary currents on the Greenland slope (the shelfbreak East Greenland Current) and the Iceland slope (the North Icelandic Jet, NIJ). The mooring data will allow us to quantify the structure, transport, and dynamics of the sEGC over a yearlong period. Following this, the second objective is to produce the first strait-wide picture of the time-varying pathways transporting dense water into the Denmark Strait, and how the transport is partitioned between the three overflow pathways. Once this is established, the third objective is to elucidate the dynamics of the upstream circulation system and assess how this impacts the transport and hydrographic variability at the sill. The aim is to determine if the ubiquitous synoptic scale variability of the DSOW at the sill is driven by upstream fluctuations in any of the pathways, and/or if hydraulic processes at the sill influence the upstream circulation. The final objective of the study is to devise a sparse mooring array that could be implemented in the future to optimally monitor the upstream sources of DSOW over interannual to decadal time scales.

This two-year project began in September 2014. Preliminary results show that the sEGC is a robust feature discernable throughout the year in the mooring record, although the current is often partially merged with the neighboring NIJ. The water masses in the two EGC branches are distinct from those in the NIJ branch, confirming that there are two sources of overflow water. In addition, the data suggest that while the total transport of the DSOW remains constant throughout the year the relative contribution of the two sources varies significantly on both synoptic and seasonal time scales.

Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period

PIs: Rui M. Ponte[1] and Patrick Heimbach[2]
[1]Atmospheric and Environmental Research (AER), Lexington, MA
[2]Massachusetts Institute of Technology (MIT), Cambridge, MA

This project extended over a period of four years (8/1/10-7/31/14) and was a joint effort between AER and MIT. A major focus of the project was on analyses of heat content variability in the Atlantic Ocean, in relation to changes in circulation, in particular in the Atlantic meridional overturning circulation (AMOC), as well as surface heat flux forcing and effects of mixing processes. The general approach was to utilize ocean state estimates produced under the ECCO (Estimating the Circulation and Climate of the Ocean) project. These estimates provide the full three-dimensional ocean state and its evolution in time and are an exact solution of a general circulation model that has been optimized, using nonlinear least squares procedures, to fit most available data within expected model and data uncertainties. As such, the solutions analyzed in our efforts are close to the data and at the same time are consistent with all the model equations and physics, allowing for computation of heat budgets with full closure and no unphysical heat sources or sinks.

Since October 2013 to the end of the project, apart from revising and publishing results in Buckley et al. (2014a), one major effort was to examine the relative roles of temperature and velocity changes in determining the advective heat transports in the North Atlantic. In this work, described in detail by Buckley et al. (2014b), anomalies in (linear) advective heat transport convergences, as well as Ekman and geostrophic contributions, are decomposed into parts due to velocity variability, temperature variability, and their co-variability. Ekman convergences are generally dominated by variability in Ekman mass transports, which reflect the instantaneous response to local wind forcing, except in the tropics where variability in the temperature field plays a significant role. In contrast, both budget analyses and simple dynamical arguments related to geostrophic advection demonstrate that geostrophic heat transport convergences due to temperature and velocity variability are highly anticorrelated, and thus their separate treatment is not insightful. In the interior of the subtropical gyre, it is argued that the sum of air-sea heat fluxes and Ekman heat transport convergences is a reasonable measure of local atmospheric forcing, and that local atmospheric forcing, so defined, explains the majority of heat storage tendency variability on all timescales resolved by ECCO (Figure 1).

Using a similarly configured version of the MITgcm, but without the ECCO adjustments, simulations in non-optimized mode were extended to 300 years using the CORE-II forcing fields and following the CORE-II protocol (six 50-year cycles were run). These simulations were part of a detailed intercomparison by Danabasoglu et al. (2014) of different model solutions under the same CORE-II protocol in terms of the mean state of the North Atlantic circulation. The hypothesis that different models subject to the same forcing would exhibit similar circulation patterns in the North Atlantic proved of limited validity.

Straneo and Heimbach (2013) provided a review of the potential impact of changes in the North Atlantic circulation on outlet glacier changes at the marine margins of the Greenland ice sheet.

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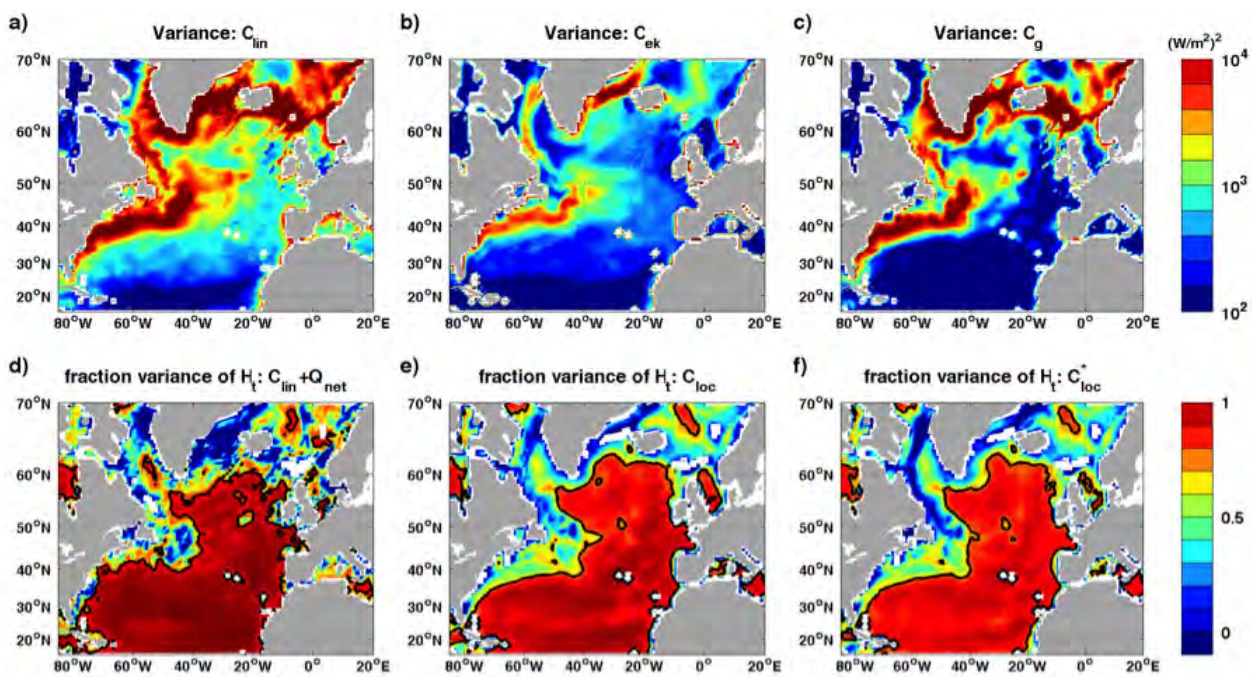

Figure 1. (a–c) Variance of monthly anomalies in advective convergence of heat for (a) linear, (b) Ekman, and (c) geostrophic terms. (d–f) Fraction of the variance in heat storage tendency explained by (d) linear advection and surface heat flux Q, (e) total Ekman advection and Q, and (f) Ekman advection associated with only velocity variability and Q. Black contours are at levels of 0.8 in (d) and 0.7 in (e) and (f).

Research Program on Modeling Future Climate Change: Effects of Increased Atmospheric Carbon Dioxide and Other Climate Forcings

PI: A. Hu
National Center for Atmospheric Research, Boulder, CO

Influence of the Continental Ice Retreat on Future Globabl Climate

The objective of this program is to study the potential impact of the continental ice retreat, including the melt of glaciers and mountain ice caps, and the Greenland and Western Antarctic Ice Sheets, on the future global climate with focus on the AMOC.

Recent results

Evidence from observations indicates a net loss of global land-based ice and a rise of global sea level. Other than sea level rise, it is not clear how this loss of land-based ice could affect other aspects of global climate in the future. Here, we use the Community Climate System Model version 3 to evaluate the potential influence of shrinking land-based ice on the AMOC and surface climate in the next two centuries, under the IPCC A1B scenario with prescribed rates of melting for the Greenland Ice Sheet, Western Antarctic Ice Sheet, and mountain glaciers and ice caps. Results show that the AMOC, in general, is only sensitive to the freshwater discharge directly into the North Atlantic over the next two centuries (Figure 1). If the loss of ice from the Western Antarctic Ice Sheet wouldn't significantly increase from its current rate, it would not have much effect on the AMOC. The AMOC slows down further only when the surface freshwater input, due to runoff from land-based ice melt, becomes large enough to generate a net freshwater gain in the upper North Atlantic. This further weakened AMOC does not cool the global mean climate, but it does cause less warming, especially in the northern high latitudes in general and in Europe in particular. The projected precipitation increase in North America in the standard run becomes a net reduction in the simulation that includes land ice runoff. But there are precipitation increases in west Australia in the simulations where the AMOC slows down due to the inclusion of land-based ice runoff.

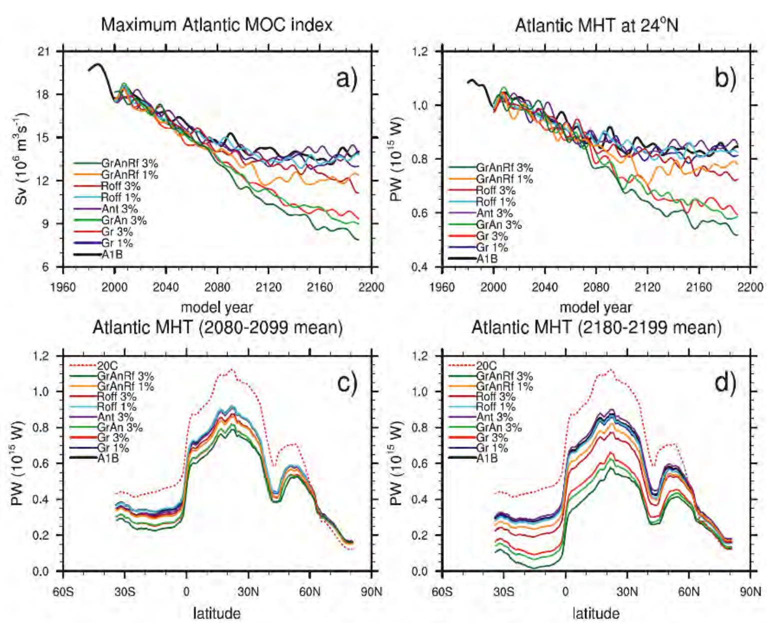

Figure 1. Changes of the MOC and MHT in the Atlantic. a) Time-evolving AMOC index; b) time-evolving Atlantic MHT at 24°N; c) the annual mean Atlantic MHT averaged over 2080-2099 for the sensitivity simulations and averaged over 1980-1999 (20C); d) the annual mean Atlantic MHT averaged over 2180-2199 for the sensitivity simulations and averaged over 1980-1999 (20C).

Uncertainty in Future Regional Sea Level Rise Due to Internal Climate Variability

The objective of this study is to investigate the impact of the internal climate variability (atmospheric and oceanic internal variability) on the projected regional and global mean sea level rise under a global warming scenario.

Recent results

Sea level rise is an inescapable consequence of increasing greenhouse gas concentrations with potentially harmful effects on human populations in coastal and island regions. Observational evidence indicates that global sea level has risen in the 20th century, and climate models project an acceleration of this trend in the coming decades. We analyze rates of future sea level rise on regional scales in a 40-member ensemble of climate change projections with the Community Climate System Model version 3 (Figure 2). This unique ensemble allows us to assess uncertainty in the magnitude of 21st century sea level rise due to internal climate variability alone. We found that the simulated regional sea level rise at mid-century can vary by a factor of two depending on location, with the North Atlantic and Pacific showing the greatest range. This uncertainty in regional SLR results primarily from internal variations in the wind-driven and buoyancy-driven ocean circulations. The AMOC plays a significant role in determining the regional sea level rise pattern in the Atlantic Ocean and could also impact the sea level rise in the Pacific.

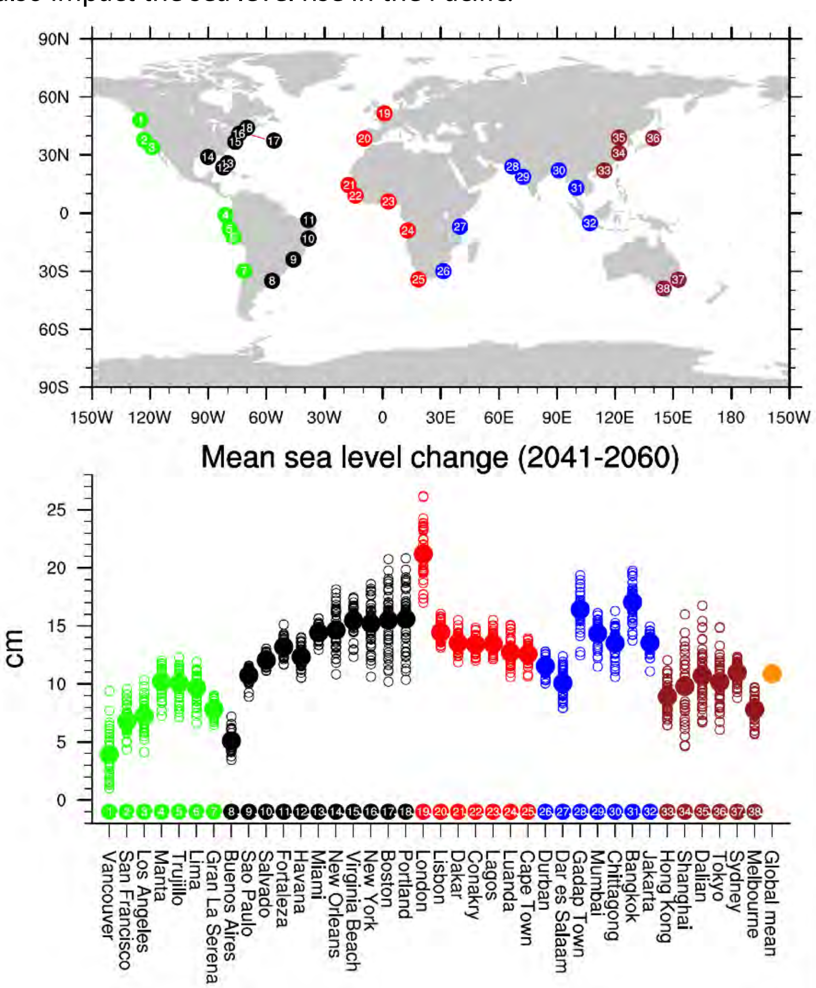

Figure 2. Simulated change in sea level (cm) between the periods 2041–2060 and 1980–1999 at selected coastal cities from the 40-member CCSM3 ensemble. The top panel shows the city locations, color-coded by region. The bottom panel shows the sea level changes using the same regional color-coding, with open circles for each of the 40 ensemble members and filled circles for the ensemble mean.

Energy Balance in a Warm World Without the Ocean Conveyor Belt and Sea Ice

The objective of this program is to investigate how the collapsed AMOC and disappearing sea ice in the polar regions will affect the global and regional heat balance.

Recent results

Under a strong global warming scenario, the global mean temperature could rise up to 10ºC, causing the global ocean conveyor belt to collapse and the summer sea ice to disappear. This will lead to profound changes in our climate system and to impact drastically the living conditions of the globe. Here we study how the global heat redistribution and regional heat balance will respond to these changes using the National Center for Atmospheric Research Community Climate System Model version 4. Results show that the collapsed ocean conveyor belt reduces the oceanic northward meridional heat transport (MHT) by nearly 60% with a minor increase in the atmospheric MHT (Figure 3). The polar amplified warming is primarily caused by the increased absorption of longwave radiation due to the increased greenhouse gases and cloudiness, and by the increased absorption of shortwave radiation due to a lower albedo associated with the disappeared summer sea ice.

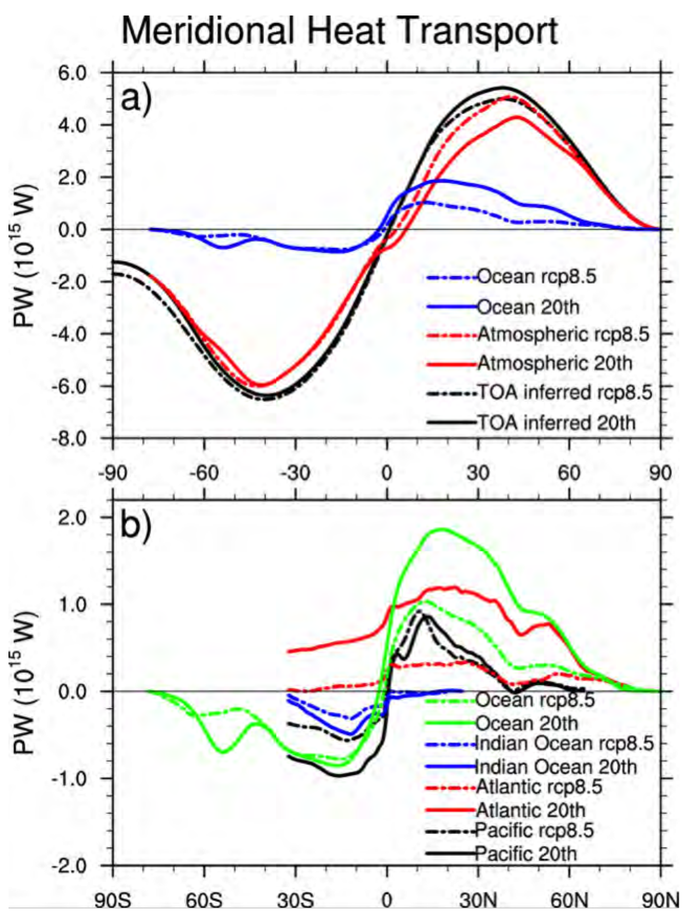

Figure 3. Meridional top of atmosphere (TOA) required atmospheric and oceanic heat transport (a) in the 20th century (mean of 1900–1999, solid lines) and in the RCP8.5 extension period (mean of 2400–2599, dashed lines); and (b) same as (a) except for individual ocean basins.

Effects of the Bering Strait Closure on AMOC and Global Climate Under Different Background Climates

The objective of this program is to investigate whether climate impacts of the Bering Strait closure/opening on the AMOC and global climate are the same or different under different background climate.

Recent results

Previous studies have suggested that the status of the Bering Strait may have a significant influence on global climate variability on centennial, millennial, and even longer time scales. Here we use multiple versions of the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM, versions 2 and 3) to investigate the influence of the Bering Strait closure/opening on the Atlantic Meridional Overturning Circulation (AMOC) and global mean climate under present-day, 15 thousand-year before present (kyr BP), and 112 kyr BP climate boundary conditions. Our results show that regardless of the version of the model used or the widely different background climates, the Bering Strait's closure produces a robust result of a strengthening of the AMOC, and an increase in the northward meridional heat transport in the Atlantic (Figure 4). As a consequence, the climate becomes warmer in the North Atlantic and the surrounding regions, but cooler in the North Pacific, leading to a seesaw-like climate change between these two basins. For the first time it is noted that the absence of the Bering Strait throughflow causes a slower motion of Arctic sea ice, a reduced upper ocean water exchange between the Arctic and North Atlantic, reduced sea ice export, and less fresh water in the North Atlantic. These changes contribute positively to the increased upper ocean density there, thus strengthening the AMOC (Figure 5). Potentially these changes in the North Atlantic could have a significant effect on the ice sheets both upstream and downstream in ice age climate, and further influence global sea level changes.

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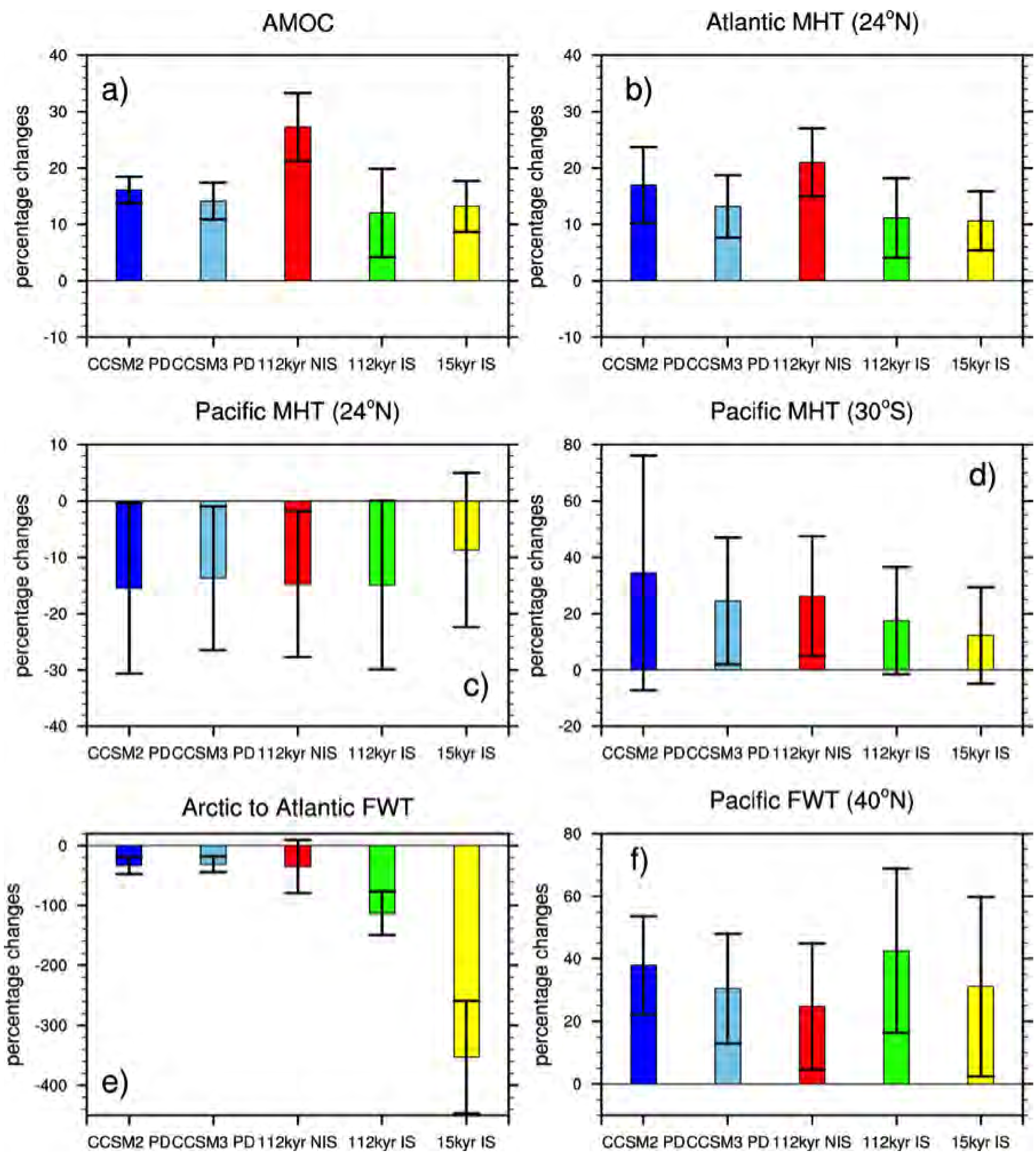

Figure 4. Percentage changes of the AMOC, Atlantic meridional heat transport (MHT) at 24°N, Pacific MHT at 24°N and 30°S, the liquid freshwater transport (FWT) from Arctic to the North Atlantic, and the FWT in the Pacific at 40°N.

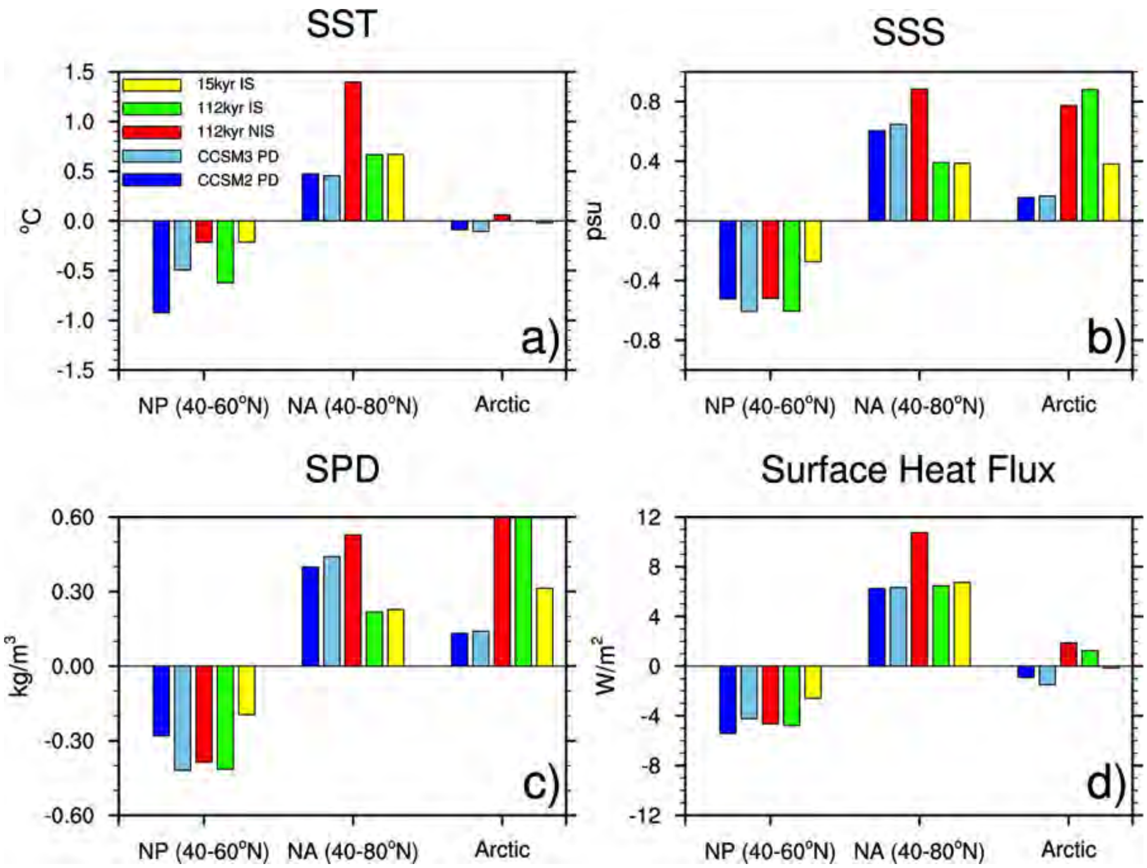

Figure 5. Regional mean sea surface temperature (SST), sea surface salinity (SSS), sea surface potential density (SPD), and total surface heat flux changes in the closed Bering Strait simulations relative to the open Bering Strait simulations in the North Pacific (NP, 40-60°N), North Atlantic (NA, 40-80°N), and the Arctic. The units for SST are °C, for SSS psu, for SPD kg/m^3, and for surface heat flux W/m^2.

Measuring Interannual Variability of the AMOC and Meridional Ocean Heat Transport at 26.5°N: The RAPID-MOCHA Array

PIs: B. Johns[1], C. Meinen[2], and M. Baringer[2]
International Collaborators: D. Smeed[3], G. McCarthy[3], E. Frajka-Williams[3], and D. Rayner[3]
[1]University of Miami, Miami FL
[2]NOAA Atlantic Oceanographic Meteorological Laboratory, Miami, FL
[3]National Oceanography Centre, Southampton, UK

The objective of this program is to continuously monitor the strength and structure of the Atlantic meridional overturning circulation and meridional ocean heat transport at 26.5°N using a basin-wide observing system. As of March 2014, we have completed a decade of observations. Funding for the array was renewed in 2014 and will continue through at least 2020.

Recent results

The mean values for the AMOC strength and northward heat transport from the 10-year time series (2004-2014) are 17.0 Sv and 1.24 PW, respectively. Both the AMOC strength and the heat transport have decreased in recent years compared to values observed prior to 2009; the five-year means for the pentad 2009-2013 were 15.6 Sv (1.34 PW) compared to values of 18.7 Sv (1.14 PW) for the pentad 2004-2008. The decline in the heat transport of 0.2 PW between these periods is significant. It is equivalent to a net decrease in surface heat flux of ~7 W/m^2 over the whole North Atlantic, north of 26.5N, and represents a net deficit in heat delivery to the North Atlantic of 1.0 PW during the last five years, nearly equivalent to one year's worth of the typical heat transport. Observations of ocean heat content (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 heat transport values recorded by the 26.5°N array.

More than 90% of the interannual variability that has occurred in the meridional heat transport is contained in the overturning component of the heat transport, while the gyre component has maintained a stable mean value. Both Ekman and Gulf Stream variability contribute to large, short-term changes in the AMOC and heat transport, including occasional heat transport reversals. However, the interannual variability of the heat transport is dominated by the geostrophic circulation and mostly by the mid-ocean heat transport. Analysis of global climate models and simpler forced dynamical models suggest that most of the interannual variability can be explained by wind-forced changes in mid-ocean circulation associated with first baroclinic mode Rossby waves that are excited by interannual wind stress curl anomalies in the central and western part of the basin.

Several improvements in the methodology for the MOC and heat transport calculations have been implemented since 2009, which have been applied retrospectively to the entire time series. These include improvements in the surface extrapolation of interior geostrophic velocities, adoption of the TEOS-10 equation of state, updated Gulf Stream temperature transport calibration, and weekly optimal interpolation of Argo and RAPID mooring data to estimate the interior temperature transport.

Online data

MOC data: http://www.noc.soton.ac.uk/rapidmoc/
Heat transport data: http://www.rsmas.miami.edu/users/mocha/

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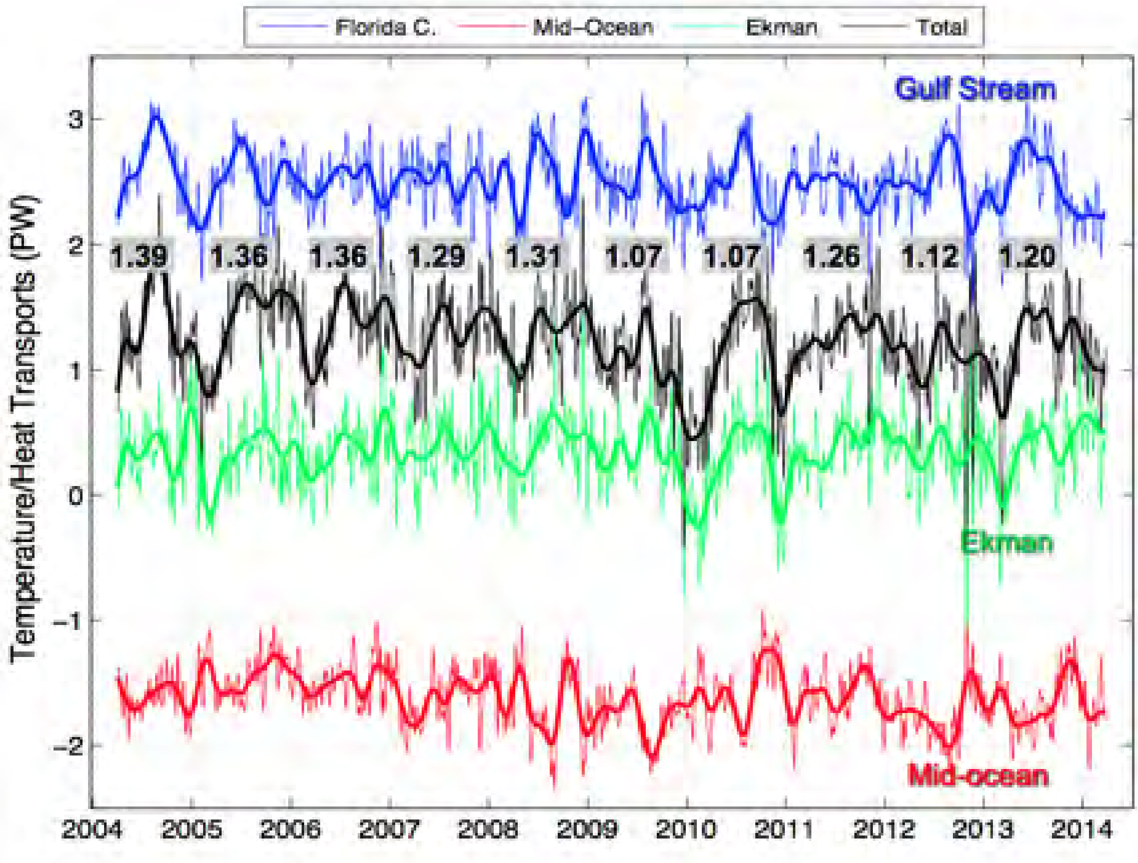

Figure 1. Time series of the meridional heat transport (black), and the contributions by the temperature transport of the Florida Current (blue), the Ekman layer (green), and the mid-ocean region from the Bahamas to Africa (red). High-frequency data are 10-day averages and smooth curves represent 90-day lowpass filtered data. Annual mean values for the heat transport during each year are shown in shaded boxes.

The Contributions of Ocean Circulation to North Atlantic SST

PIs: K. Kelly and S. Dickinson
University of Washington, Seattle WA

The goal of this project is to determine the relative importance of air-sea fluxes and ocean circulation to interannual sea surface temperature anomalies in the North Atlantic Ocean, in particular, whether advection contributes to such large-scale sea surface temperature (SST) patterns as the Atlantic Multidecadal Oscillation (AMO).

Recent results

Low frequency (interannual to decadal) variations in the ocean have typically been characterized by anomalies of SST, which have relatively long climate records. The contributions to SST are numerous: surface fluxes, mixed layer depth, entrainment, vertical mixing, Ekman pumping, and horizontal (geostrophic and Ekman) advection and diffusuion. By comparison, the contributions to the vertical integral of temperature, heat content, are relatively simple: surface fluxes and horizontal advection/diffusion. Because high-quality heat content fields are only available since 2004 (the advent of ARGO), we develop a proxy for heat content using altimetric sea surface height (SSH). Using this proxy we compare the budgets of SST and heat content.

A canonical correlation analysis on low frequency SST and heat content yields three significant modes, which are remarkably similar (not shown here), suggesting a strong correspondence between the budgets. The first mode has the familiar tripole structure, the second mode has a large positive anomaly north of 35°N, and the third mode has the signature of the Gulf Stream.

A straightforward procedure for estimating advection using velocity and gradient fields produces noisy estimates with large errors uncorrelated with observed tendencies of SST or heat content. Therefore we partitioned the budgets into three terms: tendency, surface heating, and all other terms treated as aresidual. Each of these terms was projected onto the canonical correspondence analysis (CCA) spatial modes (Figure 1).

Surface heating accounts for half or more of the first CCA mode, whereas the residual accounts for a larger fraction of the other two modes. For SST the residual is the sum of both vertical and horizontal processes, so both the magnitude and spatial structure of their contributions is difficult to assess. However, the similarity of the SST and heat content budgets suggests that the horizontal terms isolated by the heat content budget dominate the surface signature of SST. Further, this analysis suggests that the dominant contribution to both the low frequency SST and heat content is anomalous ocean circulation, rather than air-sea heat fluxes and that the historical record of SST can be used as a proxy for analyzing ocean heat content anomalies.

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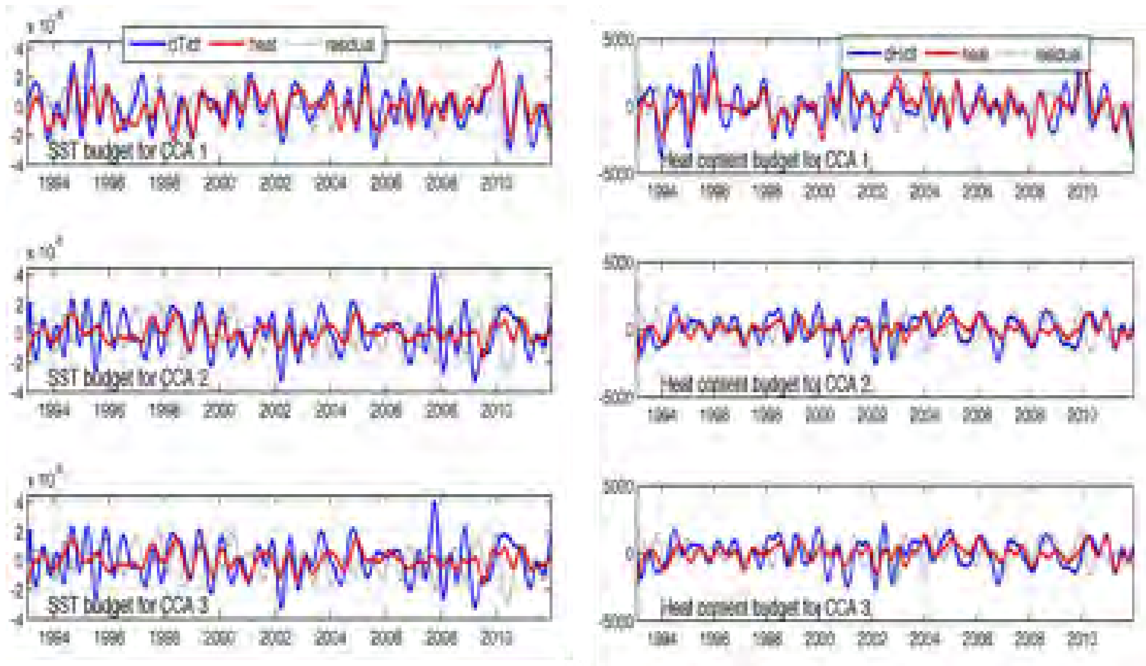

Figure 1. Comparison of SST (left) and heat content (right) budgets. A canonical correlation analysis (CCA) performed on SST and heat content yields three significant modes. The budget is partitioned into three terms: tendency (blue), surface heating (red), and all other contributions (residual, dotted) and each term is projected onto the CCA modes. For SST the variance is partitioned between heating and the residual as (top) 60/40% for CCA1, (middle) 20/80% for CCA2 and (bottom) 50/50% for CCA 3. For heat content the variance is partitioned by CCA mode as (top) 50/50% for CCA1, (middle) 33/67% for CCA2 and (bottom) 25/75% for CCA 3. For SST the residual is the sum of both vertical and horizontal processes. For heat content the residual consists only of horizontal advection and diffusion.

Sources and Impacts of Variability of the Meridional Property Transports in the Atlantic Ocean

PIs: K. Kelly and L. Thompson
University of Washington, Seattle WA

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 both observations and model output. Satellite observations of sea level, sea surface height, mass, and *in situ* based estimates of heat storage and observationally constrained surface fluxes, as well as output from both ocean only and coupled climate models, are all used in the analyses. In addition, we are examining the impact of changes in transport and storage of heat in the ocean on the atmosphere.

Recent results

An analysis of the contributions to North Atlantic sea level variability by graduate student Jinting Zhang along with Thompson and Kelly showed that on seasonal timescales, local heating explains most of the sea level signal north of 18°N while Rossby waves are important closer to the equator. In contrast, at interannual to decadal times scales, the topographic Sverdrup balance explains the signal near Greenland and Rossby waves as important between 30 and 50°N. A paper on this work will be submitted soon.

An analysis of a set of coupled model experiments, with and without perturbing the temperature in the deep subpolar gyre, shows that a positive AMOC/meridional heat transport (MHT) anomaly propagates meridionally with an advection speed consistent with the meridional flow of the deep limb of AMOC. This heat anomaly leads to heat convergence (warming) in the subpolar gyre and divergence (cooling) in the Gulf Stream region and suggests predictability of mid-latitude AMOC from temperatures upstream in the subpolar gyre. Jinting Zhang and Rong Zhang will soon submit a paper on this work.

The analysis of Kelly et al. (2014) has been extended to Atlantic heat and freshwater budgets by assimilating thermosteric and halosteric sea level, equivalent water thickness (from GRACE), and sea level anomalies. A sensitivity study using three different heat flux fields was also performed.

A lagged-correlation analysis between interannual sea surface height (SSH, as a proxy for upper ocean heat content) and surface turbulent heat flux (OAFLUX, Objectively Analyzed Air-sea Flux), and SST with OAFLUX is performed to investigate whether stored heat in the ocean below the surface layer can feedback to the atmosphere. The results show that while SST is dominantly forced by variability in the atmosphere except for in the western subtropical gyre, heat content (SSH) variability in the ocean is driven by heat transport convergences both in the separated Gulf Stream and the North Atlantic Current. In addition, the analysis suggests that the atmosphere upstream generates the heat that is released by the Gulf Stream and North Atlantic current. We are also investigating the relationship between the heat released in the Gulf Stream with the RAPID/MOCHA estimates of AMOC and MHT. A manuscript is in preparation on this work.

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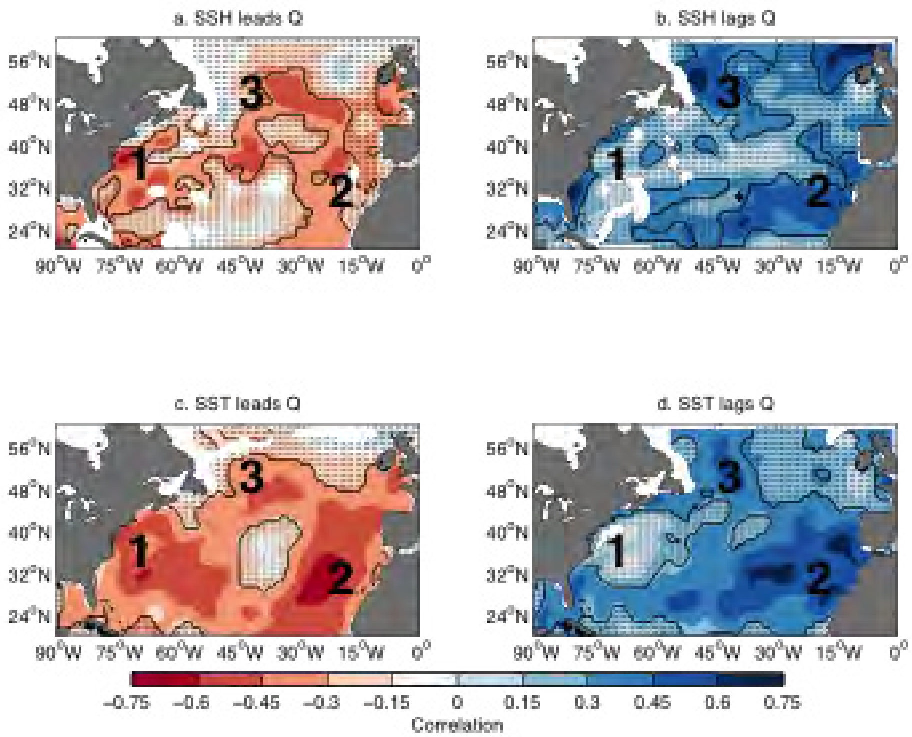

Figure 1. Lagged correlations between SST/SSH and turbulent surface flux of heat (Q). a). Minimum correlation when SSH leads Q. b) Maximum correlation when Q leads SSH. c) Minimum correlation when SST leads Q. d) Maximum correlation when Q leads SST. The label (1) in the Gulf Stream shows where Q is controlled by oceanic heat anomalies that are generated upstream off of Florida Likewise, the label (3) in the North Atlantic current shows that the released heat is generated near New Foundland. Near (2) the heat anomalies are generated locally and then those anomalies are subsequently damped.

Decadal Variability of Interacting Climate Subsystems in the Northern Hemisphere

PIs: S. Kravtsov, A. A. Tsonis
University of Wisconsin-Milwaukee, Milwaukee, WI

In this project, we study the Northern Hemisphere climate's decadal variability using data output from a suite of current-generation coupled climate models. Our primary approach is to examine networks of climate indices that generally represent coupled climate subsystems. Conceptually, we hypothesize that decadal climate shifts — defined as abrupt changes in the climates long-term state and variability that tend to happen with decadal frequency— arise as a result of collective behavior of climate subsystems due to interplay between occurrences of synchronized states and variable coupling strength within the climate network. This mechanism, which is consistent with the theory of synchronized chaos, appears to be a very robust mechanism operating in the climate system. It has been found in instrumental records, in forced and unforced climate simulations, as well as in proxy records spanning several centuries. The tendency for the climate subsystems to synchronize/couple their intra-seasonal "beats" appears to be enhanced in certain phases of the slowly varying Meridional Overturning Circulation in the Atlantic,which is, of course, dominated by the decadal time scales.

During 2014, we concentrated on identifying and comparing the properties of climatic teleconnections operating on decadal time scale in observations and simulations performed within the Coupled Model Intercomparison Project, phase 5 (CMIP5). For such a comparison, we followed the general framework developed by Wyatt et al. (2012). This framework is based on applying an objective filtering method — Multi-channel Singular Spectrum Analysis (M-SSA; Ghil et al. 2002) — to highlight the dominant multidecadal variability in a network of climate indices. Our network was comprised of indices based on surface temperature (Northern Hemisphere average temperature (NHT), Pacific Decadal Oscillation index (PDO), Atlantic Multidecadal Oscillation index (AMO), among others) and indices based on sea-level pressure (SLP), in particular the North Atlantic Oscillation (NAO) and the Aleutian Low-Pressure Index (ALPI). A variety of reanalysis data sources were used, including the 20th century reanalysis (20CR). The reanalysis-derived networks were compared to networks derived from the virtual climates produced in five independent 20th century climate realizations of the GFDL CM3 model (Kravtsov et al. 2014).

Recent results

We found that spatiotemporal structure of the simulated multidecadal variability is fundamentally different from that diagnosed in the reanalysis data sets (Figure 1). We hypothesize that these differences stem from the apparent lack of atmospheric sensitivity to multidecadal variations of surface climate in the GFDL CM3 runs, as manifested in a striking deficit of decadal-to-multidecadal variance in the NAO and SLP spectra (Figure 2).

Figure 1 notes a shared time scale and substantial phase spread among the observed indices; the latter propagation in the phase space of the observed indices is dubbed 'stadium wave.' In contrast, the GFDL simulations are characterized by the in-phase 'stadium wave' well described by the single pattern and its associated time series shown on the right for the five individual 20th century GFDL runs considered. Figure 2 shows that the simulated *multidecadal variability* is up to an order of magnitude weaker than the observed variability, while the level of interannual variability is essentially the same in models and observations,

In general, the GFDL CM3 model simulates well the amplitude of the largest-scale — Pacific and hemispheric — multidecadal variability in surface temperature, but underestimates multidecadal variability in the North Atlantic and atmospheric indices.

These results hold for other CMIP5 models and suggest that teleconnections of the AMOC multidecadal variability may be substantially muted or misrepresented in these simulations. In the next year, we plan to develop a suite of idealized models to better understand these AMOC teleconnections. These models will range from a conceptual mechanistic model of coupled delayed oscillators to a hybrid empirical-dynamical model with dynamical AMOC oscillations and empirical coupled atmospheres.

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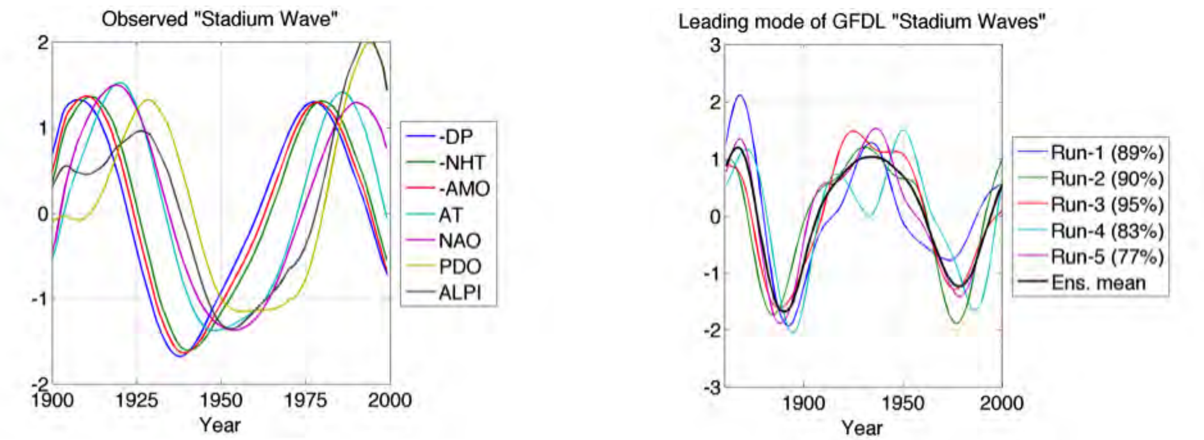

Figure 1. Leading mode of multidecadal variability (dubbed "stadium wave") in the observed (left) and GFDL CM3 simulated (right) network of climate indices (see the left panel for the list of indices used). The observed NAO and ALPI indices in the left panel were based on the 20th century reanalysis (20CR) dataset.

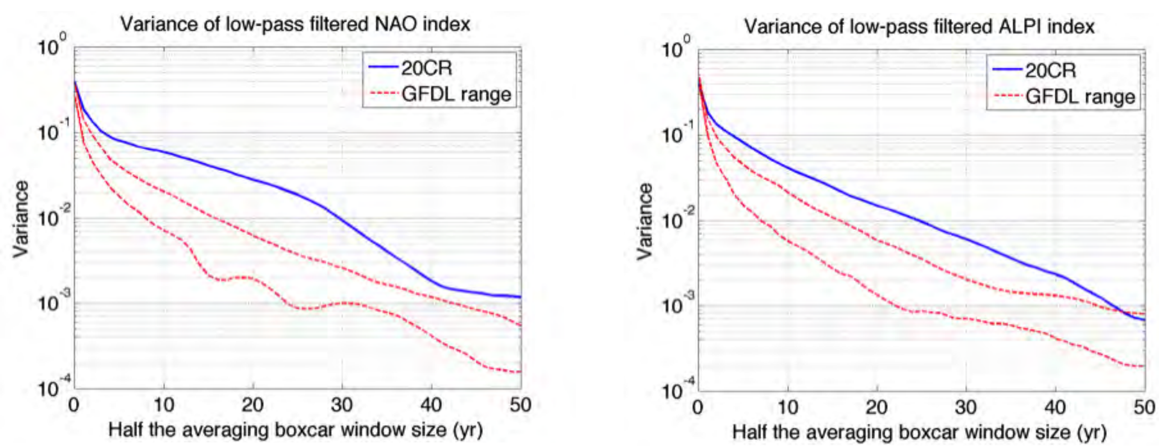

Figure 2. Spectra of the observed and GFDL simulated atmospheric indices. The spectra are defined here as the variance of the running-mean averaged time series for different window sizes. The abscissa on all plots shows half the window size in units of years, with 0 corresponding to no averaging (raw annual data), 1 to 3-yr boxcar averages, 2 to 5-yr boxcar averages and so on. The blue line shows the observed spectra based on the 20th-century reanalysis indices, and the red dashed lines show the range of spectral estimates over those for five individual 20th century runs. Index names are listed in the caption of each panel.

Variability of the South Atlantic Meridional Overturning Circulation

PIs: F. W. Landerer, K. Bentel, C. Boening, and V. Zlotnicki
Jet Propulsion Laboratory / California Institute of Technology, Pasadena, CA

Project goal

The goal of this project is to determine the feasibility of measuring Atlantic Meridional Overturning Circulation (AMOC) variations from satellite gravimetry (GRACE) via monthly ocean bottom pressure (OBP) variations. The first phase of the project uses only synthetic data to study the sensitivity of the OBP-based AMOC reconstructions, and we've limited the analysis to the North Atlantic.

Challenge

The time variable gravity signals, associated with AMOC related bottom pressure variations, are relatively small and very close to (if not smaller than) the spatial resolution that GRACE can provide (about 300 km). The zonal bathymetry gradients are steep OBP variations and are difficult to resolve with GRACE.

Recent results

We used synthetic ocean bottom pressure data from ECCO2 and establish a baseline of bottom pressure inferred AMOC transports. We then combined the ocean model data with terrestrial hydrology (total land water storage), and evaluated the errors that are introduced to the AMOC reconstruction by using a GRACE-like resolution of the bottom pressure variations, as well as the contaminating effects of land hydrology on the OBP signals.

Not surprisingly, the AMOC 'reconstruction' from GRACE-like OBP variations is degraded relative to the baseline model resolution. A major challenge is the contamination of near coastal ocean bottom pressure signal with land hydrology variations (often much stronger than ocean signals). However, our synthetic results (at two GRACE-like OBP resolutions) indicate that, despite the challenges, transport estimates from GRACE derived OBP variations provide skillful estimates over some depth intervals at specific latitudes in the North Atlantic.

Specifically we found that:

- The reconstruction from ECCO2 data (0.25° grid) works well, yielding correlations between 0.53 and 0.95, with RMS errors of approximately 0.7 Sverdrup or less (compared to 'model-truth' transports);
- The AMOC anomaly detectability is slightly reduced when we use the coarser resolution of GRACE-like ocean bottom pressure observations, but the most significant error source is the OBP signal contamination from nearby land hydrology; and
- Nonetheless, monthly AMOC variations at some latitudes can be inferred from monthly OBP via satellite gravimetry observations.
- The AMOC estimate can be further improved if we apply 'leakage corrections' on the OBP fields near the coastlines. These corrections attempt to filter and differentiate between land and ocean signals to increase the OBP signal/noise ratio.

Next steps

We will use real GRACE observations to apply our method to infer AMOC variability from 2003 – 2014, and extend the analysis of both synthetic and real OBP data to the South Atlantic.

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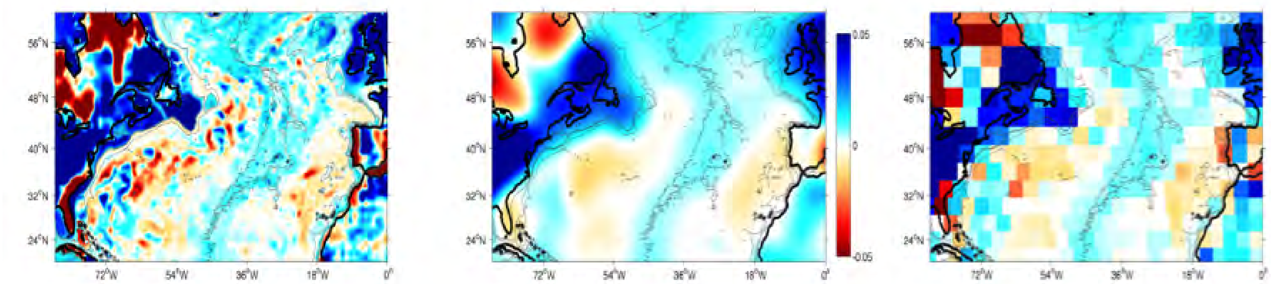

Figure 1. (left) Typical monthly OBP anomaly (December 2011) over the North Atlantic, and adjacent land water storage variations (color bar units are in m); (middle) same December 2011 anomaly, but truncated to spherical harmonic degree n=60, and smoothed with 300 km; (right) same December 2011 anomaly, but represented in 'mason' geometry and resolution. These maps exemplify the challenges of resolving near-coastal OBP features associated with the AMOC.

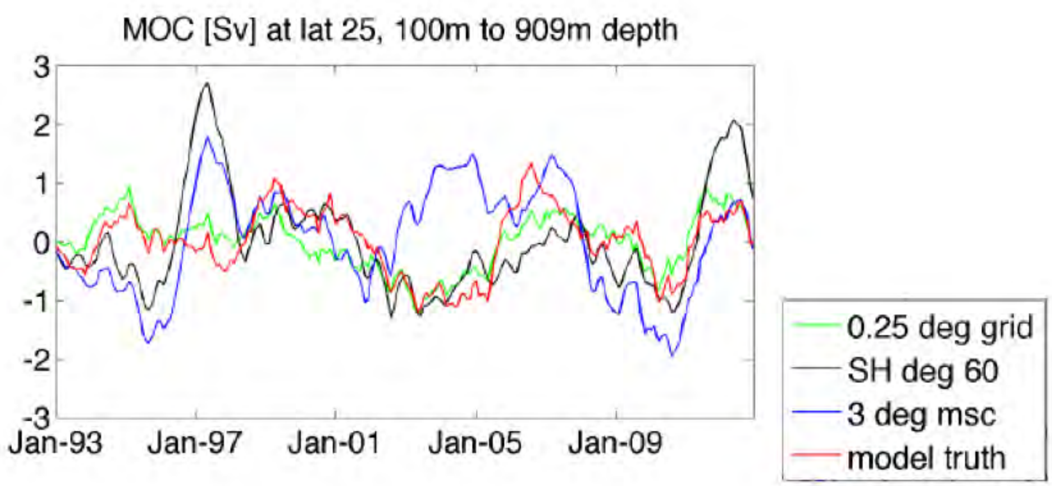

Figure 2. Time series of AMOC transport anomalies at 25°N between 100-909 m. The four lines here correspond to the various input fields (actual AMOC transport vs. the three OBP-based reconstructions (see Figure 1).

The Arctic Observing Network: Sustained Observations at the Davis Strait Gateway

PIs: C. M. Lee, J. I. Gobat, and K. M. Stafford
University of Washington, Seattle, WA
International Collaborators: B. Petrie and K. Azetsu-Scott
Bedford Institute of Oceanography, Nova Scotia

The Davis Strait observing program (Figure 1) has supported 22 published papers, with three more currently under review, three doctoral dissertations and several reports. Highlights from some of these results serve to illustrate the scientific role of long-term observations at the Davis Strait gateway.

Six-year (2004-2010) monthly-mean sections of cross-strait velocity, temperature, and salinity from moorings and gliders (Curry et al. 2014) illustrate persistent features and a seasonal cycle (Figure 2). A sharp, persistent front separates the south-going Baffin Island Current from north-flowing waters composed of the upper-ocean West Greenland Current and the deeper West Greenland Slope Current. The cross-strait position of this important front varies seasonally and interannually, which strongly impacts flux calculations (Curry et al. 2011; Curry et al. 2014). Glider-based sections provide a well-resolved measure of frontal position and structure, and quantify seasonal changes in the upper ocean, addressing two large sources of uncertainty and resolving seasonal to interannual changes in important flow structures that were previously impractical to sample.

The 2004-2013 monthly-mean net volume and freshwater flux through Davis Strait (Curry et al. 2014) has significant interannual variability, with only weak seasonality (due to phase cancellations in the water mass components that make up the mean) and no statistically significant trends. The 2004-2013 mean net volume and freshwater fluxes are -1.6±0.2 Sv and -94±7 mSv, respectively, with sea ice contributing -10±1 mSv of freshwater flux. When analyzed by water mass class, volume and freshwater fluxes show seasonality in south-flowing Arctic waters consistent with previously observed seasonality in Lancaster Sound (Peterson et al. 2012) and Nares Strait (Munchow and Melling 2008). Vage et al. (2009) assessed the impact on Labrador Sea deep convection, while Gladish et al. (2014) investigated the impact of north-going warm inflow into the Ilulissat Icefjord.

The steady accretion of long, concurrent time series at the three major Arctic Ocean gateways (Fram Strait, CAA/Davis Strait and Bering Strait) and the distributed measurements within the Arctic Ocean enable investigations of pan-Arctic freshwater exchanges and budgets. A freshwater budget that spans the period of concurrent gateway measurements (Haine et al. 2014) finds net inflow, consistent with observed and modeled increased freshwater storage in the Arctic Ocean. The study notes that shifting wind patterns could accelerate discharge through Davis and Fram straits, and emphasizes the need for continued measurements of Arctic freshwater fluxes and storage. Tsubouchi et al. (2012) and Haine et al. (2014) provide examples of high-priority science enabled by a network of sustained, concurrent observations at key locations within the Arctic system.

Torres-Valdes et al. (2013) combined velocity fields generated by an inverse model with a quasi-synoptic assemblage of hydrographic and hydrochemical data to estimate nutrient transports across all the Arctic gateways, finding Davis Strait to be the dominant pathway for nutrient exports. Baseline estimates for dissolved inorganic carbon (DIC) transport were derived using the same approach, revealing Arctic Ocean export of 225±49 TgC yr^{-1} DIC summed over all gateways, across the full depth range, with a further 5.7 TgC yr^{-1} in sea ice. In particular, this work has highlighted the important role of Davis Strait and Baffin Bay, emphasizing the need for sustained measurements of this region (MacGilchrista et al. 2014).

There are similarities emerging from Arctic-wide passive acoustic monitoring between Davis Strait and other Arctic gateways. For instance, bowhead whales in Davis, Fram, and Bering Straits are heard in these three regions when sea ice covers the moorings, emphasizing the importance of sea ice to this species (Stafford et al., 2012) Likewise, the vocal behavior of bearded seals is closely linked to ice cover in the Pacific and Atlantic Arctic (MacIntyre et al. 2013). In both Davis and Bering Strait, not only are humpback whales present late in the year, they have been recorded singing, a reproductive display normally reserved for low latitudes. Additionally, sub-Arctic species are being seen more often and later in the year above the Arctic Circle (Clarke et al. 2013; Laidre et al. 2012), which is one of the predictions for a changing climate. Lastly, a commonality of many of the datasets collected from the Arctic in the past ten years is high interannual variability in the presence of both summer and winter whales (Stafford et al. 2014). This variability underlines the importance of long-term observations so that decadal- and climate-scale changes might be distinguished from annual variability.

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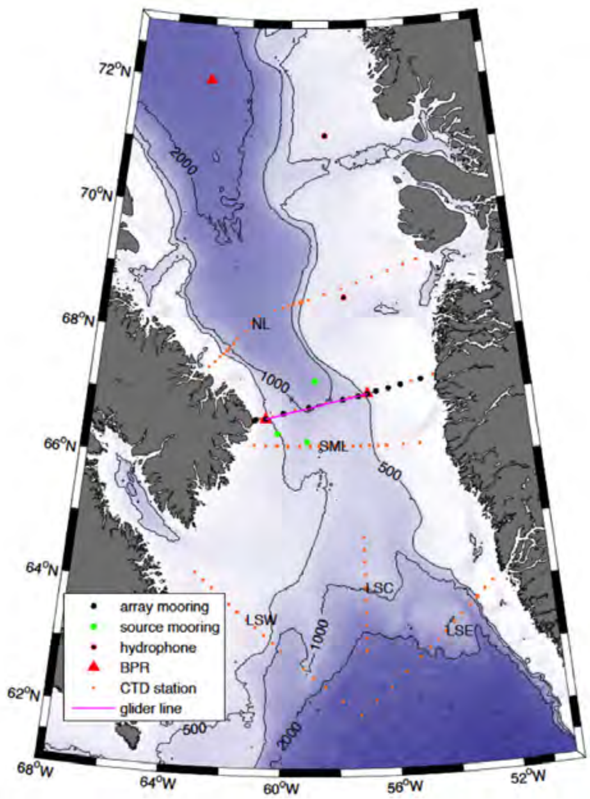

Figure 1. Current and future configuration of the Davis Strait observing array.

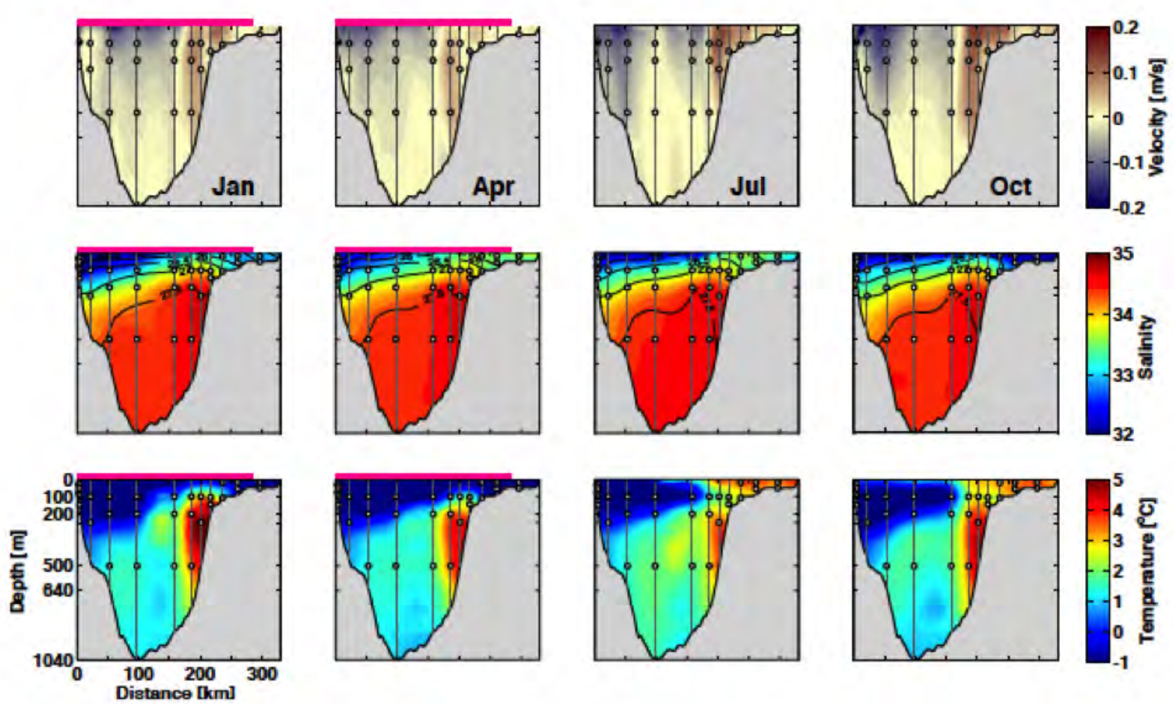

Figure 2. Monthly mean (2004-2013) analyzed sections of velocity (positive northward), salinity, and temperature. Pink overbars indicate mean ice extent and white dots mark sensor locations.

OSNAP: Overturning in the Subpolar North Atlantic Program

PIs: S. Lozier[1], B. Johns[2], A. Bower[3], R. Pickart[3], and F. Straneo[3]
International Collaborators: S. Bacon[4], S. Cunningham[5], L. deSteur[6], B. deYoung[7], J. Fischer[8], B. Greenan[9], and J. Karstenson[8]
[1]Duke University, Durham, NC
[2]University of Miami, Miami, FL
[3]Woods Hole Oceanographic Institution, Woods Hole, MA
[4]National Oceanography Centre, Southampton, UK
[5]Scottish Association for Marine Science, Argyll, UK
[6]NIOZ Royal Netherlands Institute for Sea Research, Netherlands
[7]Memorial University, St. John's, Newfoundland, Canada
[8]GEOMAR, Kiel, Germany
[9]Bedford Institute of Oceanography, Bedford, Nova Scotia, Canada

Overview

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 location of the OSNAP East and West legs purposefully melds with a number of long-term observational efforts in the North Atlantic: the Canadian repeat AR7W program in the Labrador Sea; the German Labrador Sea western boundary array at 53°N; the global Ocean Observatories Initiative node recently placed in the southwestern Irminger Sea; the repeat A1E/AR7E hydrographic sections across the Irminger and Iceland basins; and the Ellett line in the Rockall region. This observing system, in conjunction with the RAPID/MOCHA array at 26^0N and the EU THOR/NACLIM program, will provide a comprehensive measure of the North Atlantic Meridional Overturning Circulation and provide a means to evaluate intergyre connectivity in this basin. In addition to the US, the observing system has significant measurement contributions from the UK, Germany, Netherlands, and Canada. China and France plan measurement contributions beginning in the summer of 2015.

Recent results and activities

The entire OSNAP observing system (OSNAP East, OSNAP West and OSNAP Floats) was deployed in the summer of 2014 during six cruises for which UK, US, French and Canadian research vessels were employed. In addition to moorings, RAFOS floats and a glider were deployed. The first data return from the moored instrumentation will be in the summer of 2015, although data from the full array will not be recovered until the summer of 2016. Apart from a few test RAFOS floats, the floats will surface after two years. More floats are scheduled to be deployed in 2015 and 2016.

Prior to this full data retrieval, a myriad of OSNAP research projects are underway. Many of these research projects are the focus of student and post-doc projects. OSNAP students and postdocs are analyzing a host of datasets: their combined work involves 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. For a full description of these projects, see http://www.o-snap.org/partners/students-postdocs/.

To facilitate coordination among the international partners, an OSNAP steering committee has been established. One member from each participating country has been named to this committee. The responsibilities of the steering committee are to: facilitate project communication and collaborations; provide oversight of OSNAP data management and sharing; coordinate timing and agendas of both national and international meetings; and interface with the international project oversight committee. The OSNAP steering committee is in the process of identifying the international project oversight committee whose primary responsibility will be to ensure the implementation and success of the observing system by providing an independent assessment of progress. More information about the project is available at www.o-snap.org.

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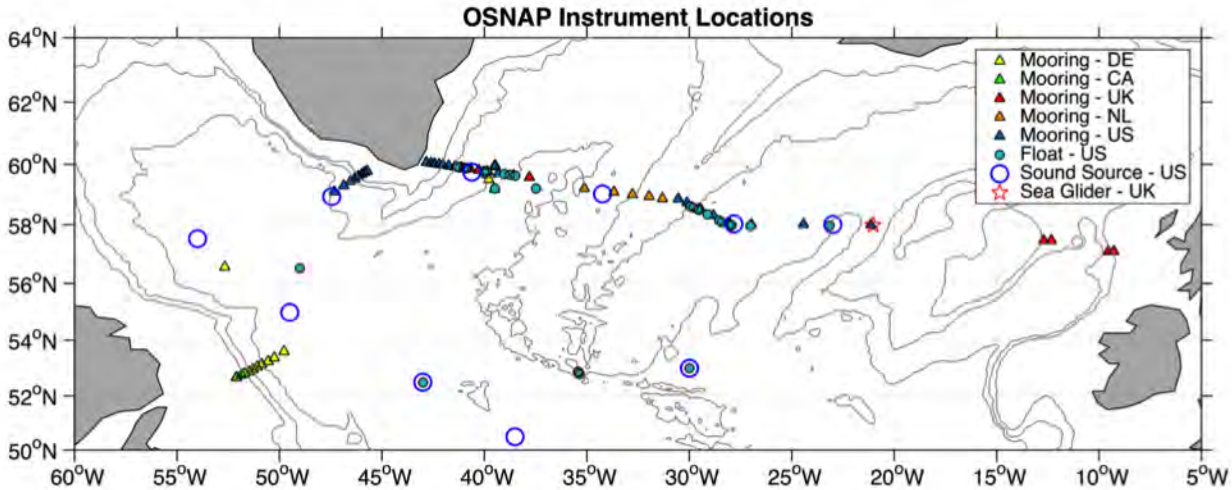

Figure 1. OSNAP observing system: From west to east: Canadian shelfbreak array and German 53°N western boundary array; US West Greenland boundary array; US/UK East Greenland boundary array; Netherlands western Mid-Atlantic Ridge array; US eastern Mid-Atlantic Ridge array; UK glider survey over the Hatton-Rockall Bank and Rockall Trough; UK Scottish Slope current array. Green dots: US float launch sites. Red star: UK Sea glider. Blue circles: US sound sources.

Southwest Atlantic MOC Project (SAM)

PIs: C. Meinen[1], S. Garzoli[2,1], R. Perez[2,1], and S. Dong[2,1]
US Collaborators: J. Sprintall[3], R. Fine[4], and G. Goni[1]
International Collaborators: A. Piola[5], E. Campos[6], S. Speich[7], I. Ansorge[8], and M. Roberts[9]
[1]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
[2]University of Miami, Miami, FL
[3]Scripps Institution of Oceanography, La Jolla, CA
[4]RSMAS/Univ. of Miami, Miami, FL
[5]University of Buenos Aires and Argentine Hydrographic Service, Buenos Aires, Argentina
[6]University of Sao Paulo, Sao Paulo, Brazil
[7]University of Brest, Brest, France
[8]University of Cape Town, Cape Town, South Africa
[9]Oceans and Coasts, Cape Town, South Africa

The Southwest Atlantic MOC ("SAM") project is designed to measure both the warm-upper and cold-deeper flows associated with the Meridional Overturning Circulation (MOC) with an array of four pressure-equipped inverted echo sounder (PIES) moorings deployed near the western boundary at 34.5°S in the Atlantic. The SAM program began in March 2009 and it is designed to be a first building block, coupled with Brazilian, French, South African, and Argentine efforts, towards a future complete trans-basin MOC observing array in the South Atlantic. The SAM array also augments an existing NOAA long-term program that estimates meridional volume and temperature transports using quarterly trans-basin high-density expendable bathythermograph sections along nominally 35°S. The SAM data is 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 sections from the coast to the location of the near shore instruments and along the PIES array during joint cruises. The NOAA SAM array has now collected more than four years of PIES data, and the array has been completely recovered and redeployed (in December 2012) with batteries that will last through 2016. In December 2012, our Brazilian partners essentially doubled the number of moored instruments with new deployments, and our French partners then doubled the number of moored instruments again when they deployed a comparable moored array on the eastern boundary in September 2013. Finally, our South African partners will be further augmenting the eastern array in late 2014 – so a trans-basin MOC array at 34.5°S is taking shape (e.g. Ansorge et al. 2013).

A publication based on the first two years of SAM data, together with contemporaneous data from a pilot French array on the eastern boundary, was published in December 2013 in the *Journal of Geophysical Research* (Meinen et al. 2013). This article was highlighted in both the journal and *EOS*. The 20-months of data used in this study shows that the variability of the basin-wide MOC at 34.5°S is roughly comparable in magnitude to (or perhaps slightly larger than) that observed in the longer 26.5°N and 16°N moored array records, and this variability is driven roughly equally by changes on the western and eastern boundaries at time scales ranging from days to a few months.

Another publication related to the goals of SAM, funded by NOAA, was published in July 2014 (Dong et al., 2014). This article diagnoses the possible causes for differences in how models and data reproduce the seasonal variations of the MOC at 34.5°S. The results indicate that the weak seasonal cycle in the model geostrophic transport can primarily be attributed to excessively strong baroclinicity below the surface mixed layer, whereas the observations show a strong vertical coherence in the velocity down to 1200 m. This study was motivated primarily by results from trans-basin expendable bathythermograph sections along 34.5°S, however it also provides very useful information for analyzing SAM data and observations from the related international projects.

During the first year of a related model-data research project, the fate of the Deep Western Boundary Current (DWBC) in the South Atlantic has been analyzed and the results are the basis for a paper presently under review (Garzoli et al. 2014). In this study, historical and new observations including hydrographic sections, Argo data, and chlorofluorocarbon measurements, are examined with two different analyses of a global ocean-only numerical model to trace the pathway of the DWBC through the South Atlantic. The results show that when the very energetic, eddy-dominated, DWBC reaches the Vitória-Trindade Ridge (~20°S), the flow branches due to conservation of potential vorticity. Both observations and model experiments indicate that the main portion of the flow continues along the continental shelf of South America in the form of a strong reformed DWBC, while a smaller portion, about 20%, is advected towards the interior of the basin. It is hypothesized that this eastward motion results from eddy thickness flux divergence, due to overlying Agulhas Ring decay and enhanced mixing caused by the energetic eddy field at the Vitória-Trindade Ridge.

Online data

More information and the raw data from the NOAA instruments is available online:

www.aoml.noaa.gov/phod/research/moc/samoc/sam/

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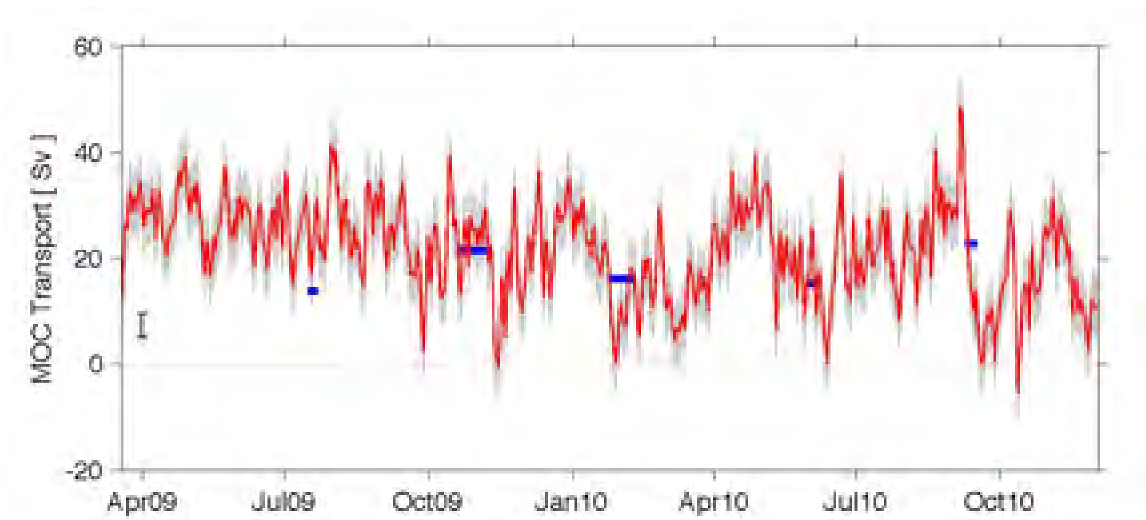

Figure 1. Time series of Meridional Overturning Circulation (MOC) volume transport (red line) over time at 34.5°S determined from the NOAA SAM array data together with the French GoodHope pilot array data. Also shown (gray line) are the error bars for the MOC estimates, as well as concurrent MOC estimates determined by expendable bathythermograph transects (blue bars) collected by the NOAA High-density XBT project where the horizontal length of the bars indicate the time range over which the transect was collected. Figure modified from Meinen et al., (2013).

A Linear Stochastic Analysis of Model Diversity in AMOC Dynamics

PIs: C. Penland[1], D. MacMartin[2], C. McColl[3,1], L. Zanna[4], L. Hartten,[3,1] and E. Tziperman[5]
[1] NOAA Earth Systems Research Laboratory, Boulder, CO
[2]California Institute of Technology, Pasadena, CA
[3]CIRES, University of Colorado, Boulder, CO
[4]University of Oxford, Oxford, UK
[5]Harvard University, Cambridge, MA

The variability of the Atlantic Meridional Overturning Circulation (AMOC) differs greatly among the separate coupled General Circulation Models (GCMs). Even within the same model, AMOC variability can be considerably different, depending on the CO2 scenario. Statistical techniques explicitly employing linear assumptions were used to document and characterize these differences in parallel investigations, results of which were recently presented at the 2014 AMOC meeting held 9-11 September in Seattle, WA.

In the first project, we used Linear Inverse Modeling (LIM) to weigh the relative importance of heat flux (HF) and freshwater flux (FW) to the AMOC as represented in two coupled GCMs, the GFDL ESM2M and the NCAR CCSM4. These models were chosen as examples of the contrast between strongly periodic and highly chaotic representations of AMOC in coupled GCMs. We found that the strongly periodic AMOC in ESM2M (not shown) is an internal oscillation that, once set off, is little affected by variations in HF and FW. In contrast, the CCSM4 relies heavily on these fields in order to maintain AMOC variability.

We represent AMOC variability by the annually averaged, zonally averaged stream function anomalies from which not only the climatology, but also the Ekman component, has been subtracted. Augmenting this field, hereafter ψ_{NoEck}, with HF and FW, we used a combination of lagged and contemporaneous covariance statistics to estimate the propagator matrix $\mathbf{G}(\tau)$ for the three-variable system over a time τ. The right singular vector ϕ of $\mathbf{G}(\tau)$, suitably normed, is the initial condition giving rise to the maximum amplification of ψ_{NoEck}, i.e., the optimal initial condition for growth. We normalized ϕ to unity and estimated the importance of HF and FW to the propagation of ψ_{NoEck} by operating $\mathbf{G}(\tau)$ and modifications thereof on ϕ.

In Figure 1, the red curve is the Euclidean norm of ψ_{NoEck} as a function of lead time for ESM2M and CCSM4 using the (ψ_{NoEck}, FW, HF) field. We repeated estimation of ψ_{NoEck}, successively suppressing interactions of 1) HF with ψ_{NoEck} (blue curve in Figure 1a,b), 2) FW with ψ_{NoEck} (green curve) and 3) both FW and HF with ψ_{NoEck} (purple curve) in $\mathbf{G}(\tau)$. For the ESM2M, the variance amplification is maximized at three years (Figure 1a), consistent with a period of about 12 years. The amplification is only slightly dependent on whether or not HF and FW are allowed to interact with ψ_{NoEck}. Further, the contribution to the variance of ϕ by ψ_{NoEck} is very close to unity, indicating that FW and HF contribute very little to the optimal initial condition for growth. In contrast, ψ_{NoEck} contributes less than two-thirds of the variance of ϕ in CCSM4 (Figure 1b). Interactions of HF and FW with ψ_{NoEck} strongly affect the amplification of ψ_{NoEck}, and this amplification occurs at smaller timescale than that in the ESM2M.

These results immediately present two questions, which are subjects of present work: 1) how can we decide which scenario is closer to the truth, and 2) how do dynamics operating on sub-annual timescales affect our results? We shall approach the first question by projecting Mercator reanalysis data onto basis patterns appropriate to each model and, using the LIM dynamical description of each model as a simulator, compare hindcasts with verification. The second question requires analysis of monthly model output to estimate subannual forcing of ψ_{NoEck}. We expect results corroborating studies by other researchers, presented in Seattle, indicating that sub-annual variability played a substantial role in the low-frequency evolution of AMOC.

In the second project, we considered the ESM2M model configured in both pre-industrial control and 4xCO2 conditions. In the former, there is a strong peak in the power spectrum of variability at both 45°N and 26°N. However, in the high-CO2 case, these peaks are either greatly reduced or nonexistent (see Figure 2), while at 60°N there is a spectral peak that was not present in the pre-industrial control case.

Understanding these differences is important for understanding the impact of AMOC on the atmospheric state under future climate change, as well as giving more insight into the physics underlying AMOC variability. A key question is whether the difference in characteristics of variability is due to a shift in the internal ocean dynamics due to the change in the mean state, or due to a change in the stochastic forcing of the AMOC. Frequency-domain transfer function analysis can evaluate individual processes relevant to AMOC variability and distinguish between shifts in the dynamics and shifts in the forcing, illustrating that it is the former that has changed. In particular, a weaker and shallower mean AMOC in the high CO2 case results in increased stratification at 45°N, which in turn results in less variability at this latitude.

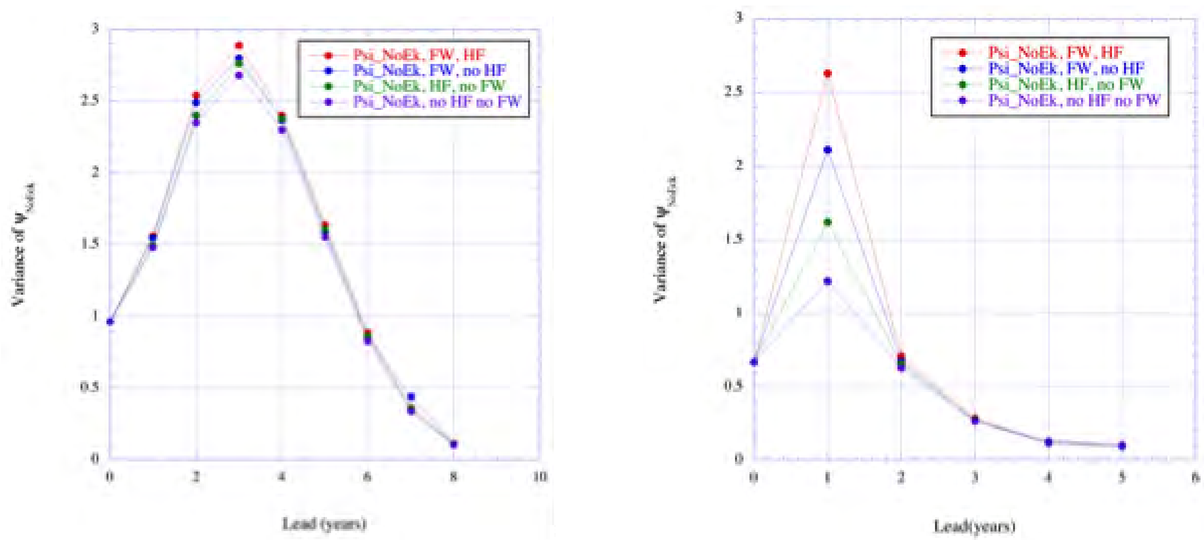

Figure 1. Euclidean norm of ψ_{NoEck} as a function of lead-time for a) ESM2M and b) CCSM4 using the (ψ_{NoEck}, FW, HF) field. See text for details.

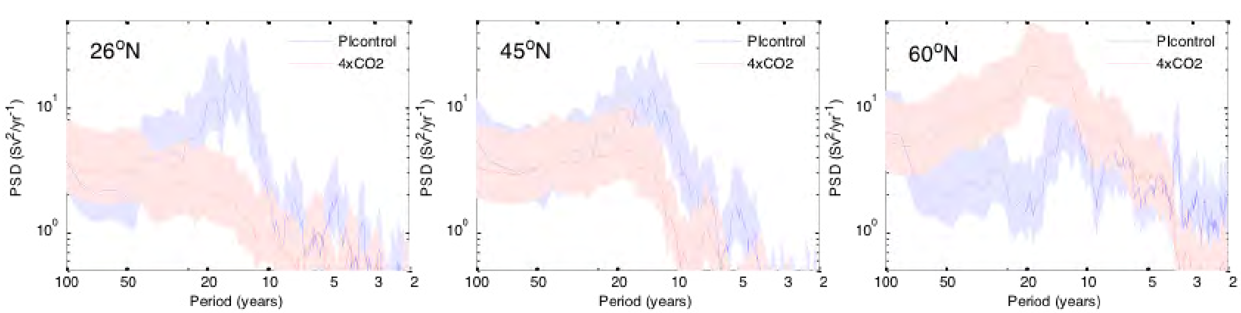

Figure 2. Power spectrum of AMOC variability in GFDL ESM2M at 26°N, 45°N, and 60°N, for the pre-industrial control and 4xCO2 simulations.

South Atlantic Meridional Overturning Circulation: Pathways and Modes of Variability

PIs: R. Perez[1,2], S. Garzoli[1,2], and R. Matano[3]
Collaborators: R. Msadek[4]
[1]University of Miami, Miami FL
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
[3]Oregon State University, Corvallis, OR
[4]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

The objective of this project, which began in September 2013, is to improve our understanding of the pathways of the upper and lower limbs of the Meridional Overturning Circulation (MOC) in the South Atlantic (SA). Our research is focused on the analysis of state-of-the-art eddy-permitting and eddy-resolving NOAA/GFDL climate model simulations, non-eddying CMIP and IPCC AR5 models including the NOAA/GFDL coarse resolution models, process-oriented numerical experiments using regional ocean models, and observations.

Recent results

During the first year of the project, we examined the fate of the Deep Western Boundary Current (DWBC) in the SA (Garzoli et al., 2014). In this study, historical and new observations including hydrographic sections, Argo data (Figure 1,) and chlorofluorocarbon measurements, are examined together with two different analyses of a global ocean-only numerical model to trace the pathway of the DWBC through the SA. When the very energetic, eddying DWBC reaches the Vitória-Trindade ridge (~20°S), the flow branches due to conservation of potential vorticity. Both observations and model experiments indicate that the main portion of the flow continues along the continental shelf of South America in the form of a strong reformed DWBC, while a smaller portion, about 20%, is advected towards the interior of the basin. It is hypothesized that this eastward motion results from eddy thickness flux divergence due to overlying Agulhas Ring decay and enhanced mixing caused by the energetic eddy field at the Vitória-Trindade ridge.

We have also developed a nested model of the SA circulation using the Agrif version of the Regional Ocean Modeling System (Combes and Matano,\ 2014). In this model setup, a high-resolution "child" model (1/12°) is embedded into a coarser resolution "parent" model (1/4°). In addition to the model development during the first year of the project, we completed two numerical simulations. The first simulation, which is the benchmark, was spun-up for 20-years and run in a diagnostic mode for another 20-years. This experiment will be used to investigate the sensitivity of the SA circulation (surface, intermediate, and deep) to changes in the model configuration (e.g., bottom topography, wind stress forcing, mixing parameterization). Preliminary assessment of slightly modified version of this model shows good agreement with observations (Combes and Matano 2014; Guerrero et al., 2014; Matano et al., 2014). To determine the pathways of the main water masses in the SA, we released passive tracers at different density levels of the model. For example, we released tracers at the Agulhas Retroflection region to show the pathways of the Indian Ocean waters in the SA. Many of the Agulhas eddies persist throughout the basin and can be tracked until they impinge on the eastern boundary of South America and, on occasion, to the Brazil/Malvinas Confluence.

Lastly, using observations and simulations by the NOAA/GFDL CM2.5 high-resolution, eddy-permitting, coupled climate model and an ocean-only (CORE forced) version of the same model, we analyzed the sensitivity of the seasonal cycle of the maximum northward volume transport by the MOC to wind forcing at the latitudes of the RAPID/MOCHA array (nominally 26.5°N) and the developing SAMBA array (nominally

34.5°S). Observation-based estimates of the annual cycle of volume transport by the MOC suggest that both geostrophic and directly wind-driven Ekman components contribute to the annual cycle in observations, and are in (out of) phase at 26.5°N (34.5°S), leading to very different total MOC seasonal cycles. Although the model simulations are able to reproduce the observed total MOC seasonal variations at 26.5°N, none of the model simulations are able to reproduce the observed geostrophic seasonal variations at 34.5°S leading to an overly strong total MOC seasonal cycle. Using a two-layer idealized ocean model (Zhao and Johns 2014), we are investigating whether the weak geostrophic seasonal cycle in the coupled model and ocean-only simulations in the SA is due to excessively strong baroclinicity below the surface mixed layer in the models.

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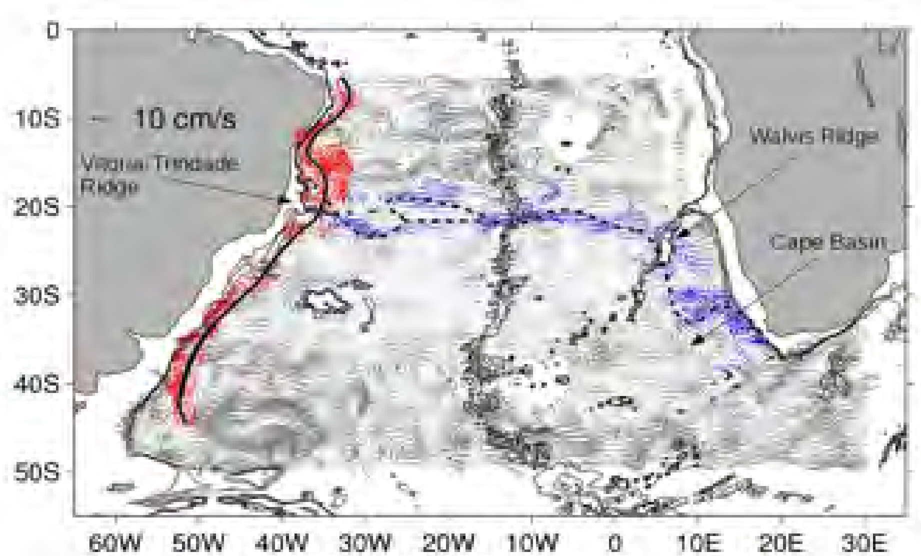

Figure 1. Velocity field at 2000 dbar derived from Argo data. Red highlights the strong southward flow along the western boundary; blue indicates the eastward velocity originating near the Vitória-Trindade ridge. Black lines: 2000, 2500 and 3000 m isobaths. Solid curves highlight the pathways of the DWBC along the South American coast. Dashed lines indicate regions where the pathway is less well developed as it moves to the interior of the basin.

Variability of the South Atlantic Subtropical Gyre

PIs: R. Perez[1,2]
Collaborators: R. Msadek[3]
[1]University of Miami, Miami FL
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL
[3]NOAA Geophysical Fluid Dynamics Laboratory, Princeton NJ

The objective of this NASA-funded project, which began in May 2014, is to improve our understanding of the South Atlantic (SAtl) subtropical gyre and its connection to the Atlantic Meridional Overturning Circulation (AMOC). The rate at which heat is transported northward versus stored by the SAtl subtropical gyre is of great importance, as the gyre plays a significant role in the establishment of oceanic teleconnections, and changes occurring in the South Atlantic alter the AMOC. As part of this study, the time-variability of the SAtl subtropical gyre will be investigated through analysis and interpretation of satellite and *in situ* data, synthesis products, OFES (ocean general circulation model for the Earth simulator) ocean-only model simulations, and state-of-the-art eddy-permitting and eddy-resolving NOAA/GFDL coupled climate simulations.

The overall goals of this project are two-fold: a) to describe the evolution of the SAtl subtropical gyre over the past two decades in the surface and intermediate waters; and b) to improve our understanding of the mechanisms that control the variability of the SAtl subtropical gyre - and the currents that delineate the boundaries of the gyre - on interannual to decadal timescales. Specifically, we will characterize the time-mean and time-varying components of the Brazil Current, South Atlantic Current, Benguela Current, Agulhas leakage, and South Equatorial Current, and ascertain whether the primary mechanisms and sources responsible for the variability of each of those currents are the same as the mechanisms that govern the gyre variability.

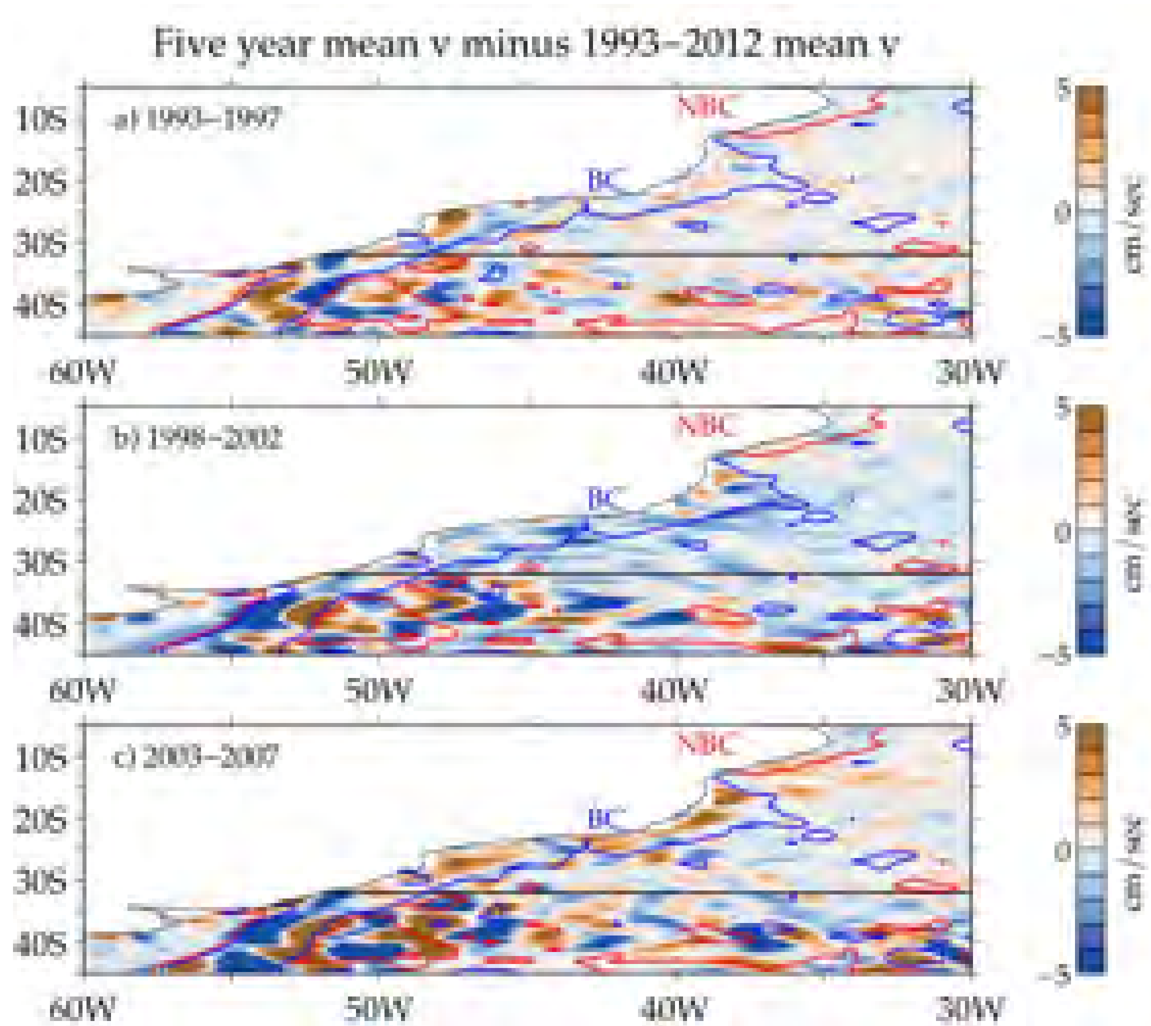

Figure 1. Five-year mean meridional velocity estimated from the Lumpkin and Garzoli (2011) drifter-altimetry synthesis, with 1993-2012 mean meridional velocity subtracted (color shading). The blue (red) contour line indicates 5 cm/sec southward (northward) flow in the 1993-2012 mean, and these contours delineate the mean locations of the Brazil Current (BC) and North Brazil Current (NBC). The black horizontal line identifies the latitude 32°S.

Denmark Strait Overflow Water: A New Paradigm for the Origin of the Deep Western Boundary Current

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

The objective of this program is to directly measure the pathways and properties of the source waters for the Denmark Strait Overflow Water (DSOW). Specifically, we seek to determine the origin, pathway, and transport of the newly discovered North Icelandic Jet (NIJ), the dynamics that are responsible for its formation, and its contribution to the flow through Denmark Strait.

Recent results

A mooring array was deployed across the northern part of the Denmark Strait, roughly 200 km upstream of the sill, from August 2011 to August 2012. The array consisted of 12 moorings positioned between the Greenland shelf and the Iceland shelf. This was a collaborative effort between four institutions (three of them international), and the data return was excellent. One of the primary aims of the array was to identify the major currents in the strait and quantify the equatorward flux of dense water comprising the DSOW.

On the western side of the strait the surface-intensified East Greenland Current (EGC) flows equatorward along the shelfbreak (Figure 1). On the Iceland slope the separated branch of the EGC also flows equatorward, alongside the NIJ, which is mid-depth intensified (centered near the 650 m isobaths). In the mean, the NIJ and separated EGC appear as a single current, but synoptically they are often separate features (the separated EGC meanders laterally in time). All three currents transport DSOW equatorward. The mean transport of overflow water above the sill depth is 1.2 Sv for the shelfbreak EGC, 0.6 Sv for the separated EGC, and 1.2 Sv for the NIJ. The sum (3.0 Sc) is on par with the transport of DSOW measured at the sill (Jochumsen et al. 2012). Contrary to the previous notion that most of the overflow water is transported southward along the Greenland slope, our results indicate that 60% of the dense water approaches Denmark Strait from the Iceland slope. The two branches of the EGC advect Atlantic-origin water, while the NIJ transports Arctic-origin water. Notably, while the total overflow transport remains constant throughout the year, the fraction of Atlantic-origin water versus Arctic-origin water varies significantly in time. This suggests that hydraulic processes may be dictating the amount of water being drawn into the strait via each component in order to keep the net transport constant.

We have also published results related to air-sea exchange and convection in the Labrador and Nordic Seas, the role of wind-driven upwelling in the formation of under-ice blooms in the Arctic Ocean and the influences of ridges or islands in a basin interior on the mean and time-dependent behavior of western boundary currents.

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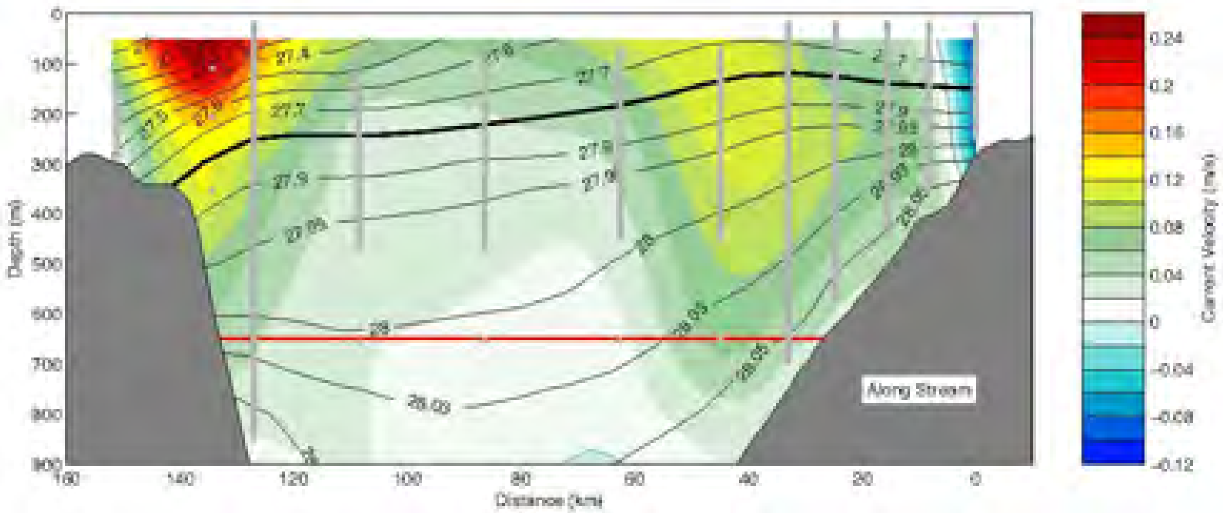

Figure 1. The yearlong mean along-strait velocity (color, m/s) overlain by the mean potential density (contours, kg/m3). The top of the DSOW layer is delineated by the 27.8 isopycnal (thick black contour), and the thick red line indicates the depth of the sill. The locations of the velocity measurements are marked by the grey dots.

The Atlantic Water Boundary Current in the Eastern Arctic: Composition, Transport, Variability, and Dynamics

PI: R. S. Pickart
Woods Hole Oceanographic Institution, Woods Hole, MA

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.

Recent results

Our project is entitled the Atlantic Water Inflow Experiment (ATWAIN), which is an international collaboration between six institutions: Woods Hole Oceanographic Institution (WHOI), Institute for Marine Research in Bergen, Norway, Norwegian Polar Institute, University of Svalbard, University of Tromsø, and Institute of Oceanology Polish Academy of Sciences. Together, we deployed eight moorings across the Atlantic water (AW) boundary current near 30°E (Figure 1a) for a one-year period, from September 2012 to September 2013. WHOI provided four of the offshore moorings in the array (Figure 1b). Unfortunately, the mooring on the upper slope was lost (presumably destroyed by fishing activity), and the motorized profiler on the offshore-most mooring malfunctioned. However, the rest of the moorings returned full datasets (including all four

WHOI moorings), and the lateral coverage across the AW boundary current is still excellent. 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 processing of the shipboard conductivity-temperature-depth (CTD) data and vessel mounted ADCP data is completed. The calibration and processing of the mooring data are still ongoing.

During the deployment cruise, we occupied two transects across the AW boundary current. Taking the AW to be within the density range 27.70–27.97 kg/m^3 and warmer than 2°C (following Rudels et al. 2005), the transport of the current during the first occupation was 1.7 ± 0.5 Sv, and for the second occupation it was 1.5 ± 0.4 Sv. These are consistent with one another, but smaller than the 3.0±0.2 Sv estimated by Beszczynska-Möller et al. (2012) using data from the Fram Strait mooring array west of Spitsbergen (for the same definition of Atlantic water). It suggests that some of the warm water entering the Eurasian Basin through Fram Strait does not continue in the boundary current. One possibility is that the current is hydrodynamically unstable and consequently diminishes in transport as it flows eastward, much like the Pacific water boundary current in the Canadian Basin (von Appen and Pickart 2012). This notion is supported by the observation of an anti-cyclonic eddy of Atlantic water offshore of the boundary current during the deployment cruise. The eddy is evident as the detached lens of warm water in Figure 1b. Based on our measurements, the eddy had a width of 25-30 km and a maximum rotational speed of 10-15 cm/s. Although the highest velocities were in the Atlantic layer, the eddy had a significant barotropic component. At this point it is unknown how common these features are, but the data from the year-long mooring array should shed light on this.

There are currently no publications from this project. A manuscript is in preparation describing the results of the deployment cruise.

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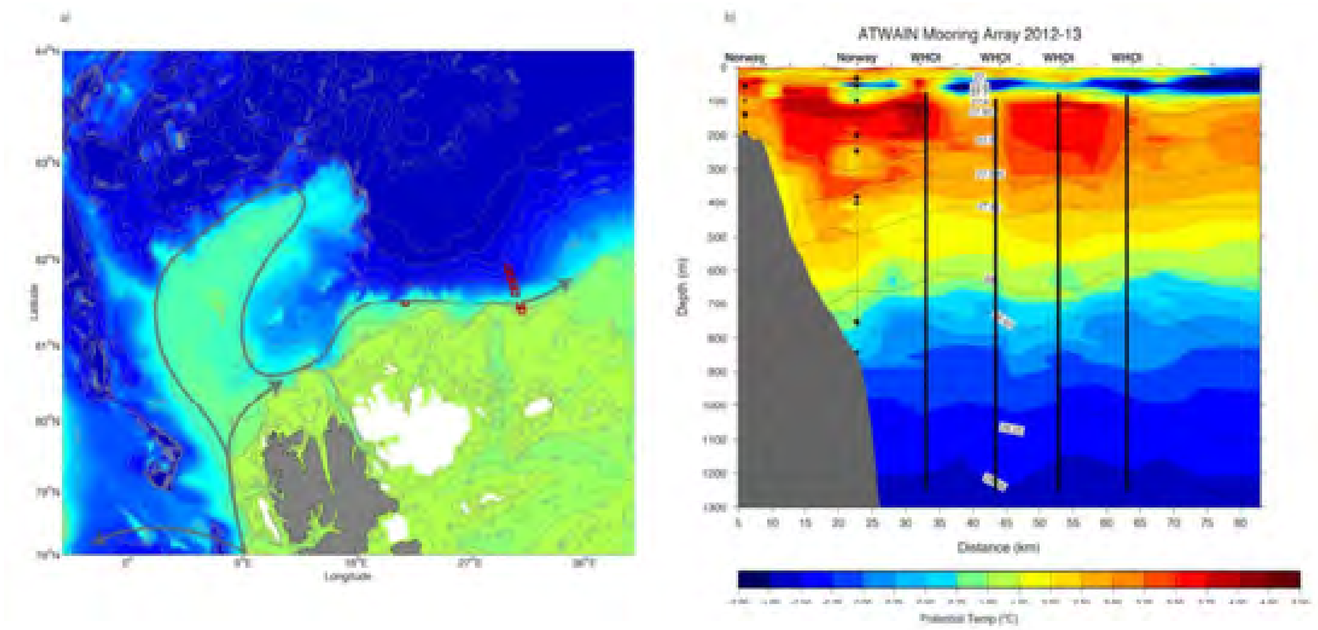

Figure 1. (a) Location of the ATWAIN mooring array near 30oE (red squares). An additional mooring was deployed upstream. The grey arrows denote the flow of Atlantic water forming the boundary current in the Eurasian Basin. (b) Cross-section of potential temperature (color) overlain by potential density (contours, kg/m3). The instrumentation of the two Norwegian moorings is indicated by the squares, and the CTD profilers deployed by WHOI are depicted by the solid lines. The region of elevated temperatures near the upper continental slope is the boundary current, and the warm lens of water offshore is the anti-cyclonic eddy.

Analysis of Eddies, Mixing and Dense Overflows of Meridional Circulation in the Climate System

PIs: P. Rhines[1] and C.Eriksen[1]
Collaborators: N. Beaird[2], E. Frajka-Williams[3], X. Xu[4], E. Chassignet[4]
[1]University of Washington, Seattle, WA
[2]Woods Hole Oceanographic Institution, Woods Hole, MA
[3]National Oceanographic Centre, Southampton, England
[4]Florida State University, Tallahassee, FL

This observational study of the hydrography and circulation near the polar front of the North Atlantic, between Iceland and Norway and in the Labrador Sea, completed its first analysis phase of roughly 20,000 vertical profiles of hydrography, bio-optics, oxygen, and derived velocity fields. The observations span six years, from 2003 to 2009, were the first to use gliders to explore dense overflows in the ocean. The provide top-to-bottom sections on the Iceland-Faroe Ridge and Faroe Bank Channel, which together account for about half (3 Sv of 6 Sv) of the dense overflows that enter the Atlantic from the Nordic Seas and Arctic, and 7 Sv/8 Sv of the warm Atlantic Water flow northward as part of AMOC. The warm branch at latitudes 60^0 - 67^0N thus carries nearly half of the peak ~ 17.5 Sv AMOC volume transport into the Nordic Seas along with about 0.3 pW temperature transport, which are more than usually seen in either climate models or high resolution ocean models. The remainder of the ~ 17.5 Sv of warm northward flow recirculates round the cyclonic subpolar gyre. The sloping interface between lower and upper AMOC waters is the polar front.

Our Seaglider observations show polar front instabilities developing in winter at the time of deep convection and enhanced westerly winds. The annual cycle of cross-frontal mixing is quite strong, and its impact on the warm AMOC branch is being investigated with high-resolution HYCOM model simulations and track-line altimetric surface currents. The dense overflows at the Iceland-Faroe Ridge (Figure1a-1d) are variable in time, and may be influenced by the strongly barotropic eddy field accompanying frontal instability. The dynamical balance in the exquisitely thin, turbulently mixing blanket of overflow water on the southern flank of the Ridge (Figre 1e) is being explored in both observations and models. HYCOM simulations by Xu and Chassignet, with lateral resolution as fine as 1/50 degree (1.5 km) are providing the numerical support. Sites of diapycnal mixing are mapped using fine-scale vertical velocity (Figure 2) and vertical strain measurements from the Seagliders, and used to improve parameterized entrainment in the model.

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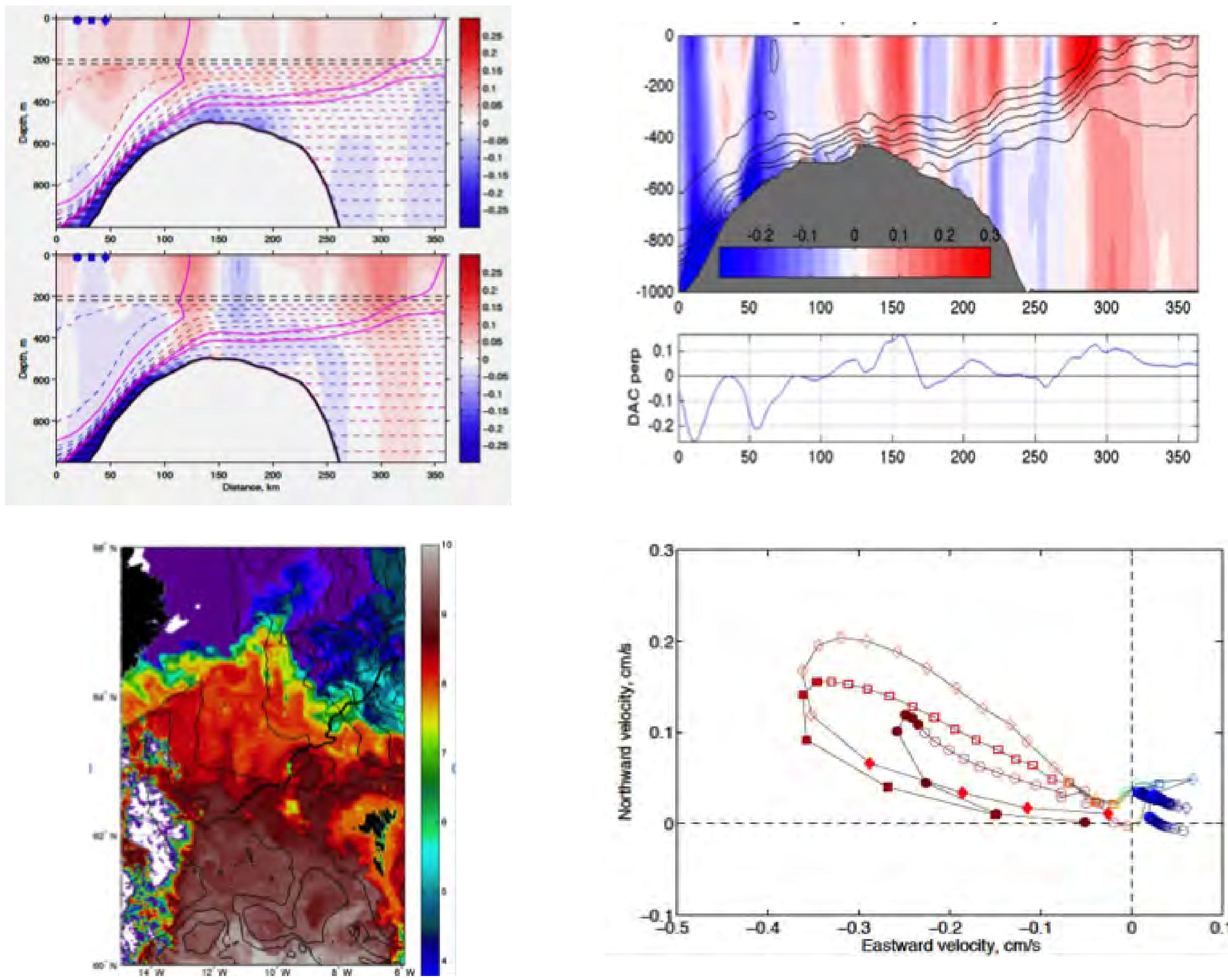

Figure 1. Top left) Time-mean HYCOM model velocities at a polar front section (top: across, bottom: along the ridge); Top right) Velocity normal to the Seaglider section as it crosses the IF Ridge. North of the IFR, at right the Faroes Current carries Atlantic Water eastward (red color) to join the Norwegian Current. It is strongly baroclinic, with a vertically thick frontal shear layer (potential density in black). South of the ridge crest, the velocity is more barotropic, reaching through the front, to the sloping bottom; depth-averaged current (DAC) along ridge plotted below; Bottom left) SST image with Seaglider track superimposed (track marked by yellow arrow). Faroe Islands at right, Iceland at upper left. Black depth contours show the IFR; Bottom right) hodograph plot, east velocity against north velocity, for 3 horizontal-velocity profiles on southwest, Atlantic flank of ridge (blue dots on 4a/b) showing downslope flow of the dense overflow layer (red dots).

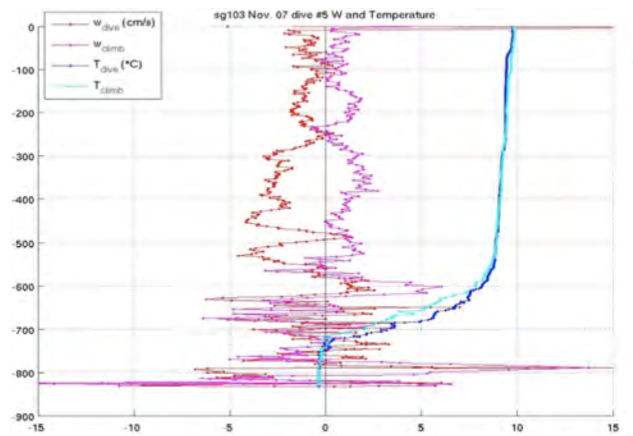

Figure 2. Mauve, orange lines: Vertical velocity of up- and down Seaglider profiles on southern Iceland Faroe Ridge, near the exit of the Faroe Bank Channel dense overflow. Intense mixing occurs in the dense overflow plume, which is tied to diapycnal mixing by Fer *et al.* 2012. Cyan, blue lines: corresponding potential temperature profiles. Depth in meters, with abscissa showing vertical velocity in cm sec^{-1} and potential temperature, ^{0}C

Improved Estimates of AMOC and Global Meridional Circulation Using Altimetry with *In Situ* Tracers

PIs: P. Rhines[1] and S. Häkkinen[2]
[1]University of Washington, Seattle, WA
[2]NASA Goddard Space Flight Center, Greenbelt, MD

Warming of the North Atlantic Ocean from 1950s to 2012 is analyzed on potential density surfaces and vertical levels, using three data reanalyses and NODC direct observations. The half-century net gain of 6.7×10^{22} J estimated in the upper 2000 m is about 30% of the global ocean warming over this period. Isopycnal layer heat content varies mostly through layer thickness and lateral extent (through heat transport convergence, rather than variability of temperature/salinity 'spice'). The subtropical mode water layer $\sigma 0$ = 26.0-27.0 expresses more than 50% of the 50-year heat gain.

The observed ocean heat content and reanalysis subsurface temperature are dominated by two modes accounting about 50-60% of all variability. The dominant mode is a trend, with a strong positive center over the Gulf Stream-North Atlantic Current (GS-NAC) region, and a weaker negative signal in the subpolar gyre. The second mode of variability is associated with the Atlantic multidecadal variability (AMV), exhibiting a negative center over the GS-NAC, and strong positive anomalies over the subpolar gyre and in the eastern basin extending to the tropics. These modes can be found also at deeper density levels, but their spatial appearance is quite different.

By dividing the upper ocean into density layers between the surface and permanent thermocline we find that the subducting subtropical mode waters ($\sigma\theta$ = 26.0 to 27.0) have gained the most heat over the 57 years, with an abrupt downturn after 2008. A significant portion of this heat gain has come from northward migration of the density surfaces. The 'hiatus' in warming during 2000-2010 occurs in the surface and subtropical mode water layers but the four datasets disagree greatly in the deeper layers. The 50-year warming corresponds to only 10-20 m of subsidence of potential isotherms, which challenges the objectively mapped data. AMV complicates trend analysis: The North Atlantic 0-30°N gains heat rather steadily while the latitudes 30-65°N have large fluctuations due to AMV variability.

Our earlier study of the association of atmospheric jet-stream blocking with warm AMV has led to a diagnosis of the acceleration of Greenland's ice-melt in mid 2000s: persistent blocking highs during summer brought warm air to the region, causing rare episodes of summer melt at the summit of the ice cap, and across southern Greenland.

A collaborative investigation is continuing, of AMOC connections between subtropics and subpolar gyre with the HYCOM Atlantic model, with Xu, Chassignet and Schmitz at Florida State University. The project is analyzing the warm water pathway through the North Atlantic Current and just below the southward dense AMOC branches flowing from the Greenland-Scotland Ridge and Labrador Sea. Atlantic model simulations, with lateral resolution as fine as 1/50 degree, are being carried out to explore mesoscale and submesoscale contributions to AMOC, particularly involving the western boundary current system.

In the subtropical Atlantic there are intricate interactions between layers of the deep circulation. North Atlantic Deep Water and Antarctic Bottom Water, for example, experience fine-scale diapycnal mixing at the Mid-Atlantic Ridge (Curry & Polzin 2013), which drives a newly discovered deep cyclonic recirculation in the lower NADW. Water-mass transformation, ocean heat content, and the projection of AMOC on the potential temperature/salinity plane ("AMOC-θS") are key diagnostic tools, as is the use of passive tracers injected into the circulation. Technical improvements to reduce numerical mixing and improve turbulent entrainment parameterization are under study. We are identifying sites of diapycnal mixing and their variability, through combination of observations and high-resolution circulation models. This understanding then can feed into low- resolution climate models.

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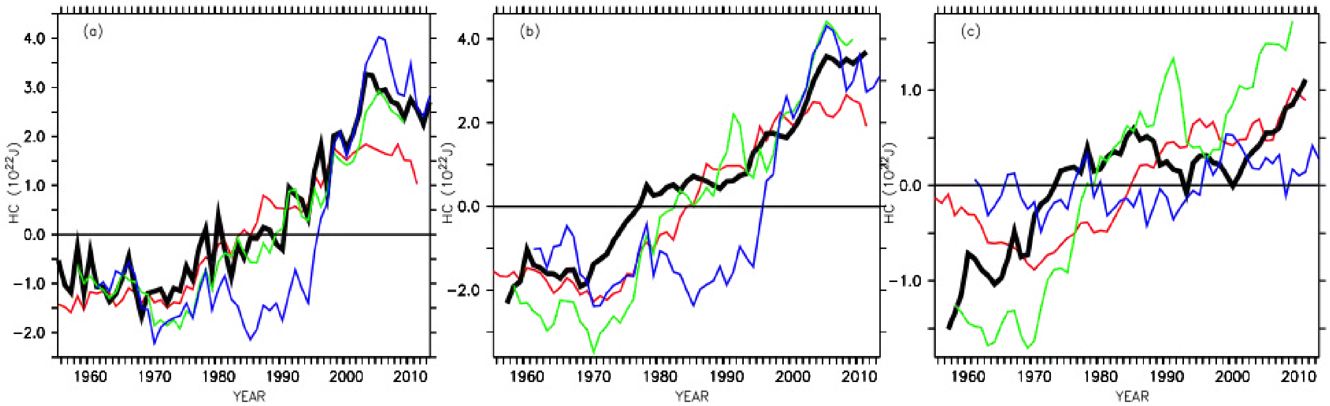

Figure 1. Evolution of the North Atlantic heat content anomaly integrated (a) 0 – 700 m and (b) 0 – 2000 m and (c) 700-2000 m from NODC (black), SODA (red), ORAS4 (Hadley Center, green) and ECDA (GFDL, blue) for 0-65°N. Units are 10^{22} J.

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

PIs: T. Rossby[1], and C. Flagg[2]

[1]University of Rhode Island, Kingston, RI

[2]Stony Brook University, Stony Brook, NY

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 very simple: to install an acoustic Doppler current profiler (ADCP) in the hull of the high-seas ferry Norröna that operates between Denmark, Torshavn in the Faroes, and Seyðisfjörður, Iceland. The 75 kHz ADCP, which reaches to > 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. Two papers have been published and two others are in preparation.

Recent results

The most significant result to emerge from the program, so far, is the different exchange patterns between the Atlantic and the Nordic Seas than previously understood, with ~0.5-1.5 Sv (1 Sverdrup = 10^6 m^3 s^{-1}) less inflow in the FSC for st < 27.8 kg m^{-3} and ~1 Sv more over the IFR. The differences are in part due to lack of adequate coverage of southward flow in the western FSC and using measured transport in the Faroe Current north of the Faroes as a proxy for the IFR inflow. These issues are discussed in the Childers et al. (2014) paper. This paper also confirms previously noted ~0.8 Sv variation in seasonal inflow in the FSC with a maximum in winter. The very high level of eddy activity in both regions underscore the need for these flux measurements to be made on a sustained and repeated basis. Another major contribution (Rossby and Flagg 2012) is the estimate of heat and salt flux, respectively. Although these were based on historical temperature and salinity data in the ICES database, they are the most accurate such estimates to date. These will soon be further improved thanks to the installation of an automated expendable bathythermograph (XBT) instrument system called AXIS (autonomous expendable instrument system). Starting in September 2013, the project has been measuring the thermal structure of both the FSC and the IFR with XBTs deployed on a monthly basis. This instrument greatly improves the ability to resolve highly structured systems (fronts and eddies) for which there are not other observing capabilities. In a paper in preparation, we will report new and improved estimates of heat flux based on these XBT data. They will be useful as very accurate constraints on allowable atmospheric heat losses in the Nordic Seas. We also expect to start operation of a thermo-salinograph shortly. This is needed to identify the various water masses between Scotland and Iceland and their variability over time.

Online data

All data collected by this project are publically available at the project website: http://po.msrc.sunysb.edu/Norrona

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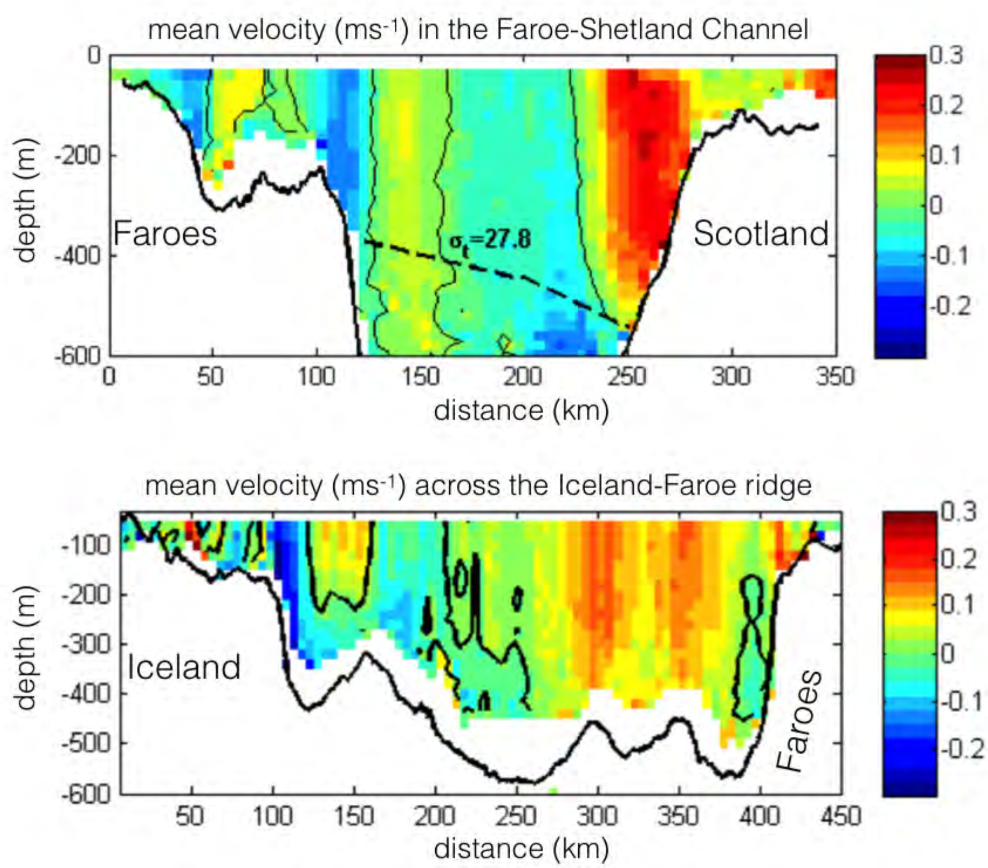

Figure 1. Mean velocity through the FSC and IFR, respectively (ms^{-1}). See Childers et al. (2014) for further details.

Transport Pathways in the North Atlantic: Searching for Throughput

PIs: I. I. Rypina[1] and L. J. Pratt[1]
International Collaborators: J-J. Park[2]
[1]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
[2]Kyungpook National University, South Korea

The objective of this program is to clarify the transport pathways in the North Atlantic, with implications for physical, chemical or biological tracers.

Recent results

At the end of their life cycle, American eel (*Anguilla rostrata*) migrate to the Sargasso Sea from freshwater habitats along the east coast of North America in order to spawn planktonic eggs. The eggs develop into larvae that then have to reach estuarine and freshwater nursery habitats along the North American coast within approximately their first year of life. A coupled biological–physical model was used to study how potential behavioral adaptations influence the ability of American eel larvae to reach near-coastal waters. Specifically, several larval swimming behaviors were investigated, including passive drift, random walk swimming, and directional navigation with and without a preferred swimming direction. Directional swimming with a randomly chosen direction improved the success rates of larvae reaching the continental shelf by more than two orders of magnitude compared to passive drift, and swimming primarily to the northwest further tripled these success rates. Success rates also substantially increased for larvae with swimming abilities even slightly above an estimated average. Notably, directional swimming resulted in a reasonable distribution of larvae along the North American shelf break, whereas other swimming scenarios left distinct gaps where no simulated larvae reached the shelf, including near the Gulf of Maine where juvenile eels are abundant. Additionally, directional swimming yielded transit times of about one year, in agreement with observations. Finally, the model supported the southwestern Sargasso Sea as the probable spawning area for American eel. A manuscript describing these results has been published (Rypina et al. 2014)

The American Eel population has been declining over the last two decades. Part of this decline is due to overfishing. However, the oceanic variability on inter-annual scales also has a direct influence on the number of larvae that are reaching the coast each year. We have been investigating the connection between the North Atlantic circulation and the success rates of American eel larvae using a coupled physical-biological model.

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Transport in the Upper Branch of the South Atlantic Meridional Overturning Circulation

PIs: C. Schmid[1] and G. Halliwell[1]
Collaborators: S. Majumder[2]
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
University of Miami, Miami, FL

This proposal is focused on computing transport indexes for monitoring the Meridional Overturning Circulation (MOC) in the South Atlantic Ocean at selected latitudes from Argo observations complemented with satellite observations and model fields. To accomplish this, a method for deriving three-dimensional fields of absolute velocity in the upper 2000 m of the ocean developed by the PI for the estimation of the climatological flow field will be employed to calculate seasonal estimates of the flow field during the Argo period. The method is based on *in situ* observations from Argo that are complemented with sea surface height from satellite altimetry (AVISO). The plan is to use these fields in conjunction with fields of the Ekman transport to derive seasonal estimates of the volume transport in the upper branch of the MOC across selected latitudes, starting in 2000. The methodology will be evaluated by comparing the estimated transports with transport estimates from independent observations: (1) the estimates based on the expendable bathythermograph (XBT) transects along 35°S that were derived four to five times a year since 2002; (2) transports across 34.5°S that are estimated from data collected by the South Atlantic Meridional Overturning Circulation (SAMOC) project; (3) transports across 26.5°N that are estimated from data collected by the Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array (RAPID/MOCHA). Two ocean model products produced by other groups will be analyzed to validate the realism of, and also to augment the scientific analysis of, the observation-based products.

This three-year project began in August 2014. Preliminary results show that the MOC transports at 35°S derived from Argo and altimetry compare well with those derived from the AX18 XBT line. When comparing monthly climatological estimates of the volume and heat transports, the values from the new estimates are about 15 to 27 Sv and 0.3 to 1.0 PW, respectively. For the XBT-based estimates, the value ranges are about 16 to 22 Sv and 0.4 to 0.9 PW, respectively. The new estimates have also been used to derive a preliminary time series of monthly estimates for the years 2000 to 2013 that reveals a significant seasonal to interannual variability of the transports.

Modeling Effects of Greenland Ice Sheet Melting on AMOC Variability and Predictability

PIs: A. Schmittner[1], A. Hu[2], S. H. Mernhild[3]
International Collaborators: D. Bi[4], S. Marsland[4], K. Dommerget[4], S. Phipps[4], J. Li[5], T. Zhou[6], P. Lin[6], R. Stouffer[7], J. Yin[8], L. Jackson[9], M. Menary[9], D. Swingedouw[10], S. Drijfhout[11], A. Abe-Ouchi[12], M. Yoshimori[12], U. Mikolajewicz[13], K. Taylor[14], M. van den Broeke[15], J. Lenaerts[15]
[1]Oregon State University, Corvallis, OR
[2]National Center for Atmospheric Research, Boulder, CO
[3]Los Alamos National Laboratory, Los Alamos, NM
[4]Center for Scientific Studies, Santiago, Chile
[4]Commonwealth Scientific and Industrial Research Organization, Australia
[5]Beijing Climate Center, Beijing, China
[6]Laboratory of Numerical Modeling for Atmospheric Sciences & Geophysical Fluid Dynamics, Bejing, China
[7]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ
[8]University of Arizona, Tucson, AZ
[9]Hadley Center, Exeter, UK
[10]Institu Pierre Simon Laplace, France
[11]Royal Netherlands Meteorological Institute, Netherlands
[12]University of Tokyo, Japan
[13]Max Planck Institute, Hamburg, Germany
[14]Lawrrence Livermore National Laboratory, Livermore, CA
[15]Utrecht University, Netherlands

The goals of this project are to quantify impacts of enhanced future melting of the Greenland Ice Sheet (GrIS) on Atlantic Meridional Overturning Circulation (AMOC) variability and predictability. The approach is to construct detailed projections of future GrIS meltwater fluxes and runoff, to incorporate those as an additional forcing in multiple state-of-the-science global climate models (GCMs) and to run those models for 100-300 years into the future.

2013-2014 activities:

- In close collaboration with researchers from Utrecht University (The Netherlands) a parametrization of future GrIS melt as a function of local temperature changes has been developed based on high-resolution regional climate modeling and observational data.
- Several Greenland Ice Sheet melt scenarios have been developed based on this parameterization. The scenarios consider high-end and intermediate greenhouse gas scenarios RCP4.5 and RCP8.5, CMIP5 multimodel-mean local temperature change projections, observed runoff and iceberg calving rates to correct for biases in the amount and seasonality of Greenland Ice Sheet runoff simulated by the individual GCMs, and feedbacks between enhanced GrIS melt and climate change by interactively calculating the amount of melt based on the simulated local temperature change using the developed parameterization.
- A range of GrIS melt scenarios has been distributed to the modeling centers around the world that are involved in the project.
- Currently researchers in five different countries are using seven to nine different GCMs to perform the different experiments.

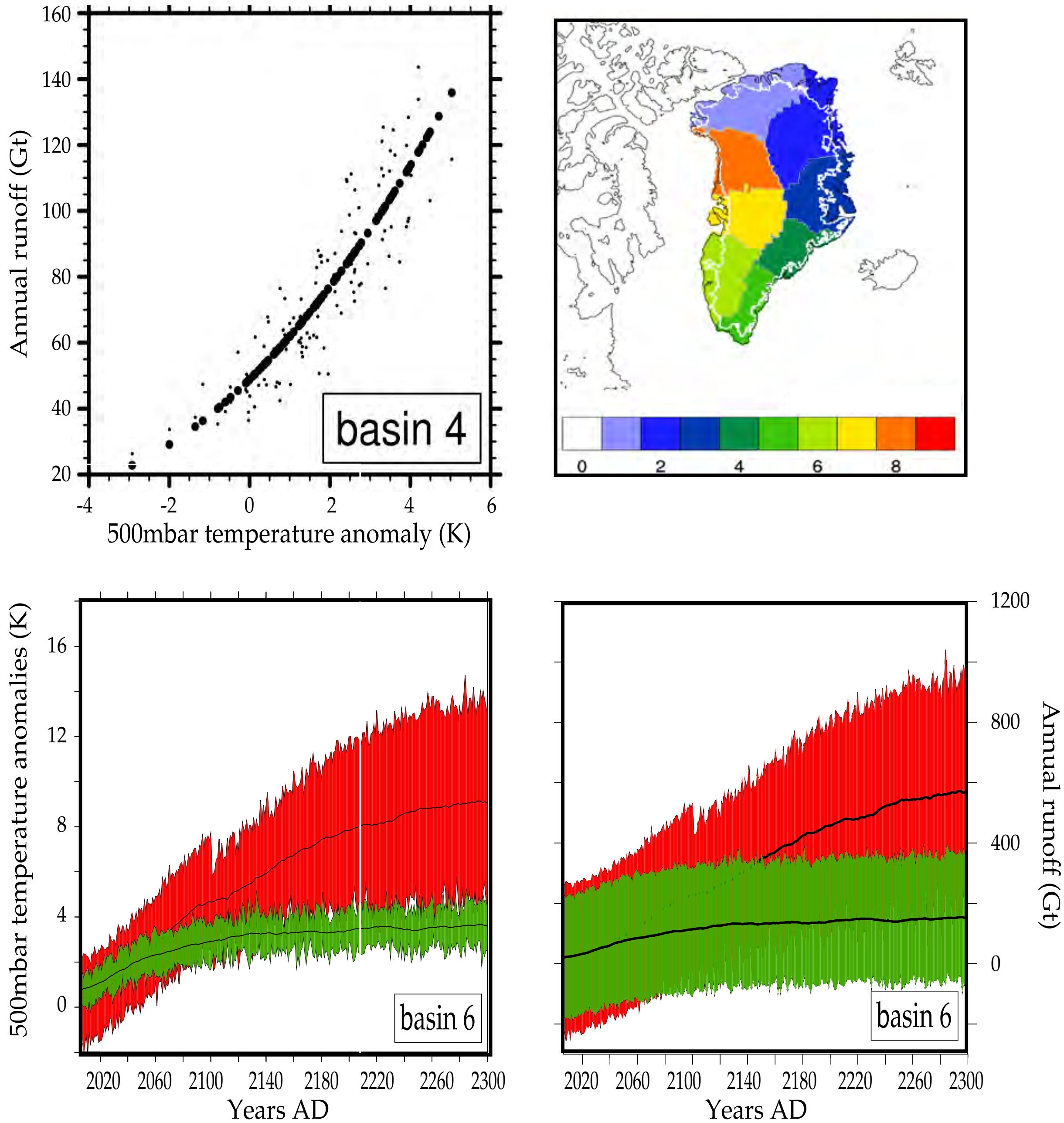

Figure 1. Top right) The eight different runoff basin of the Greenland Ice Sheet used in the project. Top left) The relationship between changes in the local 500mbar temperatures and annual mean runoff found in an historical simulation with the regional climate model RACMO2. Example shown for basin 4. Bottom left) CMIP5 multi-model-mean temperature changes at 500mbar (mean ±6) for the period 2006-2300 for RCP4.5 (green) and RCP8.5 (red). Example given for basin 6. Bottom right) Runoff projection following the developed parameterization and the CMIP5 multimodel-mean temperature changes (mean ±6) for the period 2006-2300 for RCP4.5 (green) and RCP8.5 (red). Example given for basin 6.

MOVE: Meridional Overturning Variability Experiment

PIs: U. Send and M. Lankhorst
Scripps Institution of Oceanography, La Jolla, CA

The objective of the MOVE project is to maintain an operational observing system to continuously sample the strength of the lower branch of the Atlantic Meridional Overturning Circulation (AMOC) at 16°N. The system extends from the western boundary to the mid-Atlantic ridge. The MOVE time series started in 2000, and has now returned almost 14 years of data.

The observing system consists of presently three moorings and two sets of two seafloor instruments each. The most recent field swap of instruments was in May 2013.
In October 2013, MOVE carried out fieldwork to acoustically download data from all deployed assets, without physically recovering any of them. The resulting time series (Figure 1) demonstrates substantial interannual variability, with the more recent data looking similar to the earlier years, but substantially different flow strength and vertical structure in between. Analyses are ongoing, and results were presented at the 2014 US AMOC Science Team Meeting in September.

MOVE data have been used in the "State of the Climate in 2013" report, as well as the 5th IPCC assessment report (see bibliography). A paper by Köhler et al. (2014) uses early MOVE data to examine high-frequency variability, and the project continues to maintain its website at http://mooring.ucsd.edu/projects/move/move_intro.html.

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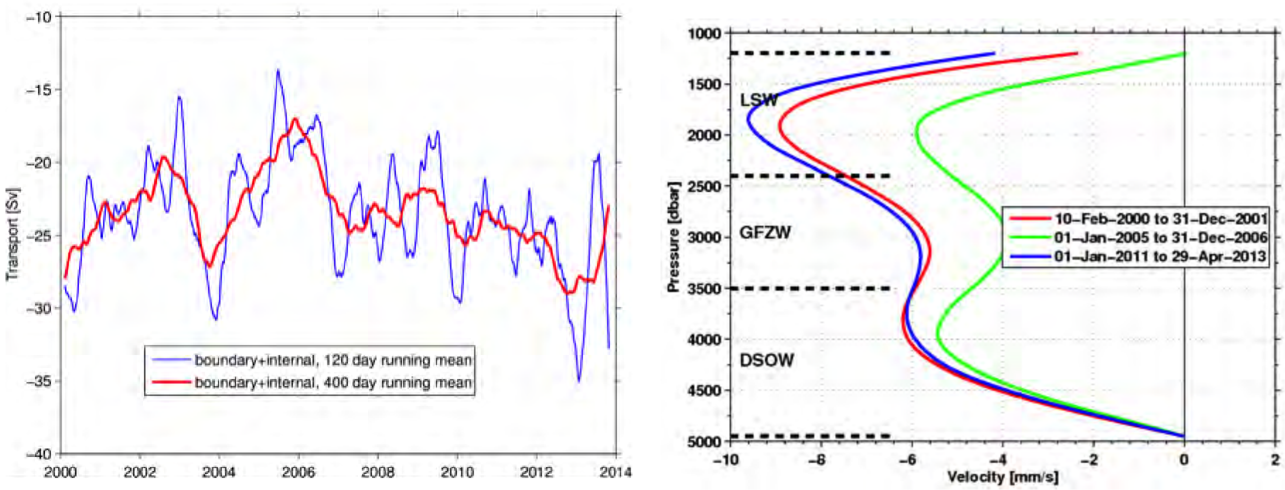

Figure 1. (Left) Water volume transport between 1200 and 4950 dbar, which is computed as the sum of the "boundary" and "internal" components of the MOVE measurements (see Send et al. 2011, for details). Different filters show interannual variability. Negative numbers indicate southward flow. (Right) Vertical velocity structure of the "internal" component for three time intervals (Feb. 2000-Dec. 2001; Jan. 2005-Dec. 2006; Jan. 2011-Apr 2013).

Forced Transients in Water Mass Transformation and the Meridional Overturning

PI: M. Spall

Woods Hole Oceanographic Institution, Woods Hole, MA

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, meridional heat transport, meridional overturning circulation, and the temperature and salinity of product waters.

Recent results

There have been two major activities in the past year:

A simple dynamical systems model of a convective basin subject to time dependent precipitation has been developed and compared with an eddy resolving numerical model. This is in collaboration with Yuki Yasuda, a graduate student at the University of Tokyo and a Fellow of the WHOI Geophysical Fluid Dynamics Summer School in 2013. The response of a convective basin to transients in precipitation depends primarily on the nondimensional frequency of the forcing, its amplitude, and how close the solution lies to a critical value of precipitation that marks transition between thermal and haline modes. The theory compares reasonably well with the numerical model calculations in terms of the amplitude and phase of the temperature, salinity, and heat flux anomalies (Yasuda and Spall 2014).

A similar approach of combining a dynamical systems model with an eddy resolving general circulation model has been taken for time-dependent atmospheric temperature over a marginal sea subject to deep convection. Linearized analytic solutions are possible, while the fully nonlinear coupled equations can be directly integrated numerically. The amplitude and phase of the convective water mass temperature and salinity, the meridional heat transport, surface heat flux, and the meridional overturning circulation predicted by the theory compare well with a series of numerical model calculations. The key response is a transition from one-dimensional behavior for high frequency forcing to three-dimensional, quasi-steady behavior for low frequency forcing. The transition frequency depends on nondimensional numbers that characterize the stability of the boundary current, strength of atmospheric forcing, and the eddy flushing time scale of the basin.

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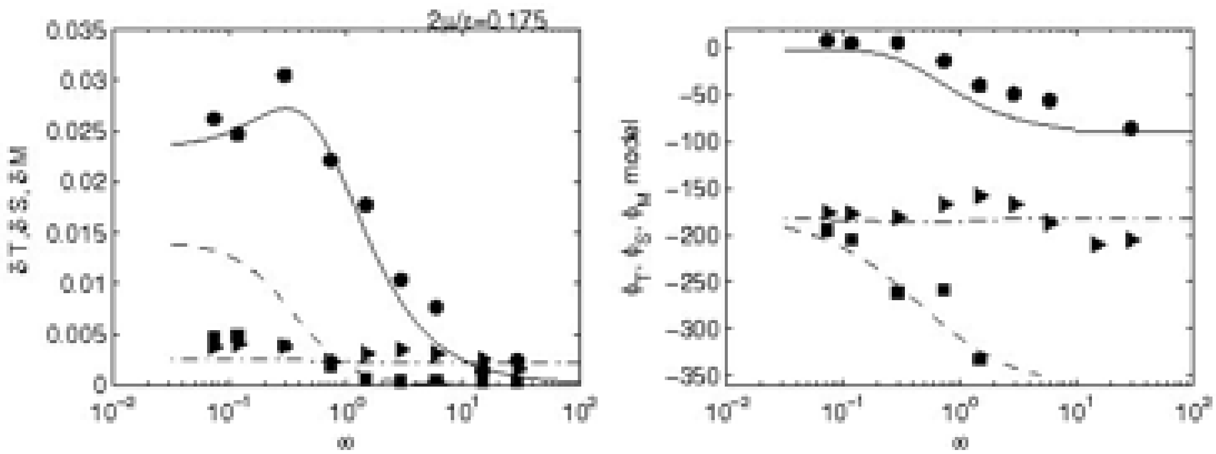

Figure 1. Comparison between theory and an eddy resolving numerical model for cases in which the atmospheric temperature varies with (nondimensional) frequency w. Left panel: nondimensional amplitude of variability as a function of forcing frequency. Right panel: phase relative to the atmospheric temperature anomaly (zero phase corresponds to a warm atmosphere). Lines are for the theory; symbols are for individual numerical model calculations with different frequency of variability in the atmospheric temperature. Solid lines and circles are for temperature of convective water mass. Dashed lines and squares are for salinity of the convective water mass. Dot-dashed lines and triangles are for the meridional overturning circulation. The parameter 2m/e=0.175 is a measure of the lateral eddy heat flux from the boundary current compared to heat loss to the atmosphere. 2m/e<<1 indicates that the boundary current is relatively unstable, roughly corresponding to the situation in the Labrador Sea. A similar set of calculations has been carried out for a more thermally-forced case with 2m/e=1.2.

Mechanisms of Freshwater Exchange Across the East Greenland Shelf

PIs: M. Spall[1] and T. Haine[2]
[1]Woods Hole Oceanographic Institution, Woods Hole, MA
[1]Johns Hopkins University, Baltimore, MD

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 Atlantic Meridional Overturning Circulation and its sensitivity to changes in atmospheric forcing and freshwater outflow from the Arctic Ocean. We plan to combine a realistic, very high resolution, regional model of the east Greenland shelf and adjacent deep ocean together with idealized, process oriented models and *in situ* observations to identify the strength, mechanisms, and sensitivity of this exchange. Processes likely important for this cross-shelf exchange include: surface and bottom Ekman layers; nonlinear eddy fluxes; local and remote wind-forcing; and wind-driven sea ice. We will diagnose the exchange in a series of realistic model runs, design experiments for the idealized model that will isolate the relevant processes for further study and understanding, and make comparisons with *in situ* mooring and hydrographic observations and remotely sensed sea ice data. We seek to gain basic understanding of what controls the flux of freshwater from the shelf to the basin interior and how it depends on external forcing (wind, outflow from the Arctic, Greenland runoff) and environmental conditions such as bottom bathymetry and ambient stratification.

Wave Processes Along 26°N in the Atlantic

PIs: Z. Szuts, and K. Martini
University of Washington, Seattle, WA

This project analyzes the MOCHA/WBTS/RAPID mooring data along 26°N in terms of wave motion at periods of hours to years. Particular focus is given to the western boundary, which is a key location for wave transformations hypothesized by theories of general circulation or by numerical models. An observational description of these waves and their transformations requires sustained measurements over a large area, an attribute now met by the 10+ years of data collected by seven full depth moorings from the 26°N array.

The first and fundamental activity to perform at the start of this project in 2014 was to reprocess the over eight years of data records at a higher sampling rate from the raw measurements. The high frequency single instrument records were combined following methods from the MOCHA/WBTS/RAPID project. Vertical modes were calculated using previously developed techniques (Szuts et al. 2012).

With reprocessed data available, the next task was a general description of the signals in the measurements. At the most basic, if energy contained at a specific frequency and vertical shape changes from one mooring to another, then we know that the wave regime has changed. This can be seen in frequency spectra of vertically-integrated potential and kinetic energy (Figure 1). At sub-inertial frequencies, potential energy is large in the center of the western basin (WB5) and decreases towards the boundary. The same decrease is seen in the component of kinetic energy that is perpendicular to the boundary. This decrease is most noticeable at the low frequencies known to have large eddy/wave signals. In contrast, energy at intermediate frequencies (periods of 1 to 10 days) increases closer to the boundary. This intermediate frequency band is a distinct wave regime and will be a key focus for continuing research.

At supra-inertial frequencies, kinetic and potential energy diminish from the offshore (WB4) to the onshore mooring (WB1) indicating the internal wave field is modified across the western boundary. Analyses of tidal and near-inertial band motions show a weak internal wave field that is dominated by propagating waves generated at other remote locations. Semidiurnal motions are small, baroclinic tidal velocities that have a weak spring-neap cycle uncoupled with local surface tides. Near-inertial motions have a seasonal cycle peaking during the North Atlantic storm season. At the western flank of the mid-Atlantic Ridge (MarW), supra-inertial potential energy is elevated near the bottom consistent with energetic internal tides. Monthly averages of semidiurnal and near-inertial band kinetic energy from 2004-2013 shows there is large spatial and temporal variability in the strength of the local internal wave field across at 26°N.

This project also supported Z. Szuts as an advisory panel member for a graduate student at the University of Southampton, Louis Clément, who was studying the impact of westward propagating eddies on calculations of overturning circulation from the 26°N array (Clément et al. 2014).

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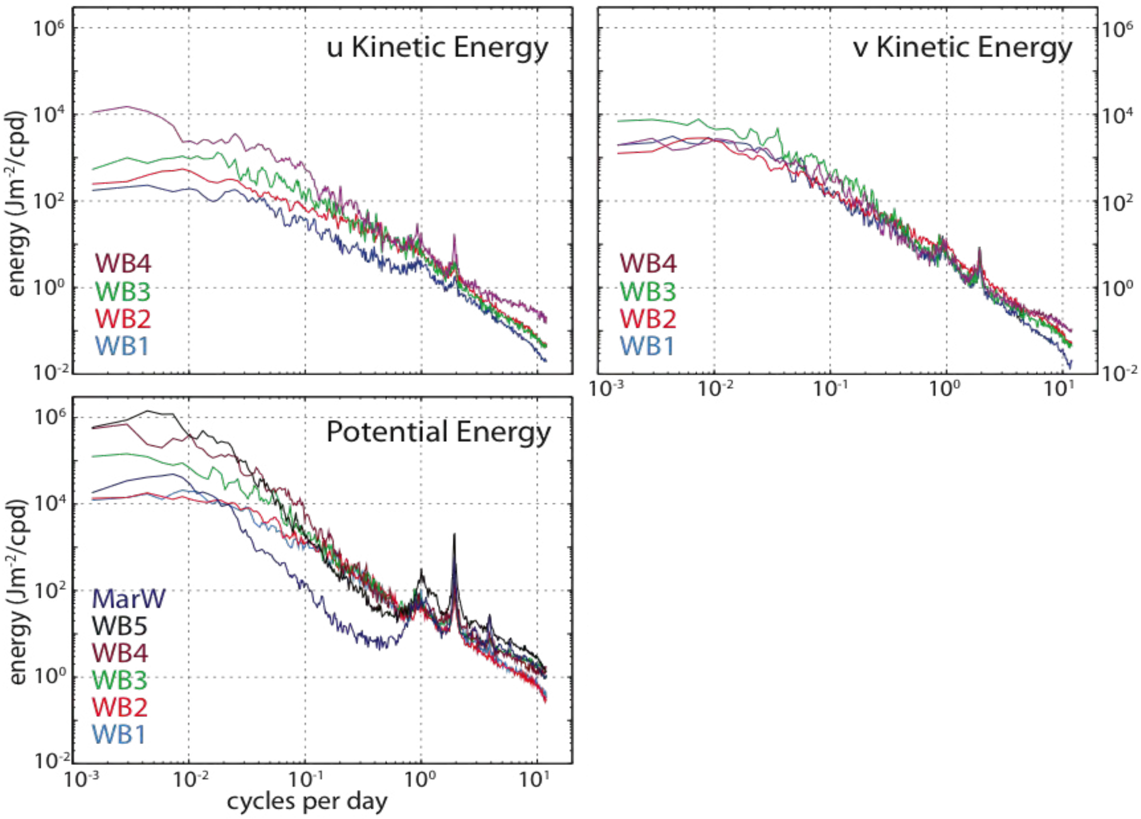

Figure 1. Frequency spectra of energy integrated through the water column from moorings along 26N, for (top left) the u component of kinetic energy, (top right) the v component of kinetic energy, and (bottom left) potential energy. The moorings are located offshore from the western boudary by: 4km for WB1, 15 km for WB2, 40 km for WB3, 90 km for WB4, and 490 km for WB5. MarW is on the western flank of the mid-Atlantic Ridge.

Line W: A Sustained Measurement Program Sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39°N

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

PIs: J. Toole[1], M. McCartney[1], R. Curry[1], T. Joyce[1], M. Andres[1], and W. Smethie[2]
1 Woods Hole Oceanographic Institution, Woods Hole MA
2 Lamont-Doherty Earth Observatory, Palasades NY
Collaborators: J. Smith[3], S. Elipot[4], C. Hughes[5], and B. Peña -Molino[6]
3 University of Miami, Miami, FL
4 Bedford Institute of Oceanography, Dartmouth NS, Canada
5 National Oceanography Centre, Liverpool, UK
6 University of Tasmania, Hobart, Australia

The Line W program seeks to document interannual transport changes in the North Atlantic's Deep Western Boundary Current and Gulf Stream and investigate their causes and consequences for the climate system using data from a sustained moored array and repeated occupation of a hydrographic section. The program will produce a 10-year-long time series of boundary current variability that will be used together with companion programs at other latitudes in the Atlantic to characterize the Meridional Overturning Circulation in this ocean. The principal research activities carried out in 2014 included the final cruise of the field program aboard *R/V Knorr* (May 1-12, 2014) during which the six moorings in the array were recovered and the hydrographic section was reoccupied (Figure 1), on-going processing and analysis of data obtained thus far, and continuation of the efforts to write-up results for journal publication. MIT/WHOI Joint Program student Isabela Le Bras, who is supported on this project, is investigating the North Atlantic's deep western boundary current and its interaction with the Gulf Stream. Finalized mooring and cruise datasets available to date have been submitted to the *OceanSites* data archive.

Online data

Line W program website: http://www.whoi.edu/science/PO/linew/index.htm

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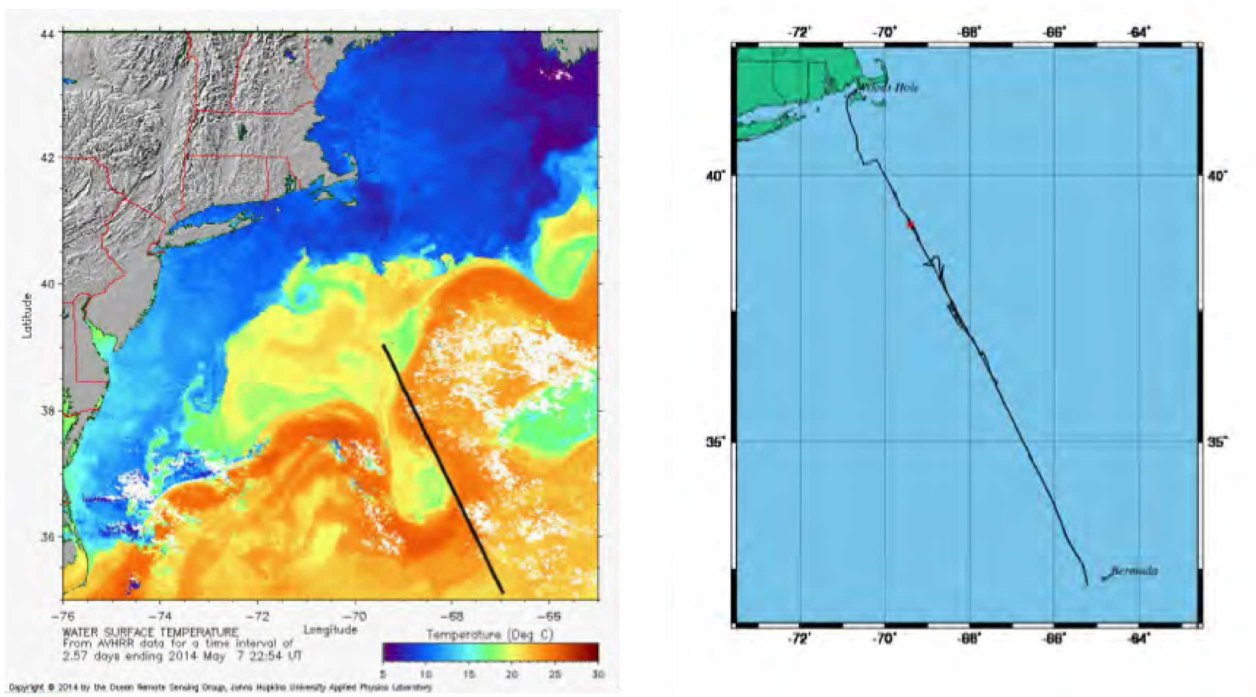

Figure 1. Sea surface temperature image from early May 2014 (left) during the final Line W cruise: *R/V Knorr* cruise 218. The cruise track is shown schematically overlaid on the SST image and in detail (right).

Collaborative Research: An Interactive Multi-Model for Consensus on Climate Change

PIs: G. Duane[1], A. Tsonis[2], J. Tribbia[3]
International Collaborators: L. Kocarev[4]
[1]University of Colorado, Boulder, CO
[2]University of Wisconsin, Milwaukee, WI
[3]National Center for Atmospheric Research, Boulder, CO
[4]Macedonian Academy of Sciences and Arts, Skopje, Macedonia

Project synopsis

This collaboration has several components but the main idea is that when imperfect copies of a given nonlinear dynamical system are coupled, they may synchronize for some set of coupling parameters. This idea is to be tested for several IPCC-like models each one with its own formulation and representing an "imperfect" copy of the true climate system. By computing the coupling parameters, which will lead the models to a synchronized state, a consensus on climate change simulations may be achieved.

Recent results

Another aspect of synchronization in climate (and my part of the project) is the synchronization of climate modes. These modes represent low-order subsystems in climate and it has been shown that they often synchronize. An important element in the theory of synchronization between coupled nonlinear oscillators is coupling strength. The theory of synchronized chaos (Pecora et al. 1997; Boccaletti et al. 2002) predicts that in many cases when such systems synchronize, an increase in coupling strength between the oscillators may destroy the synchronous state and alter the system's behavior. These ideas were initially explored in a network of four climate oscillators, namely El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the North Pacific Index (NPI), and the Pacific Decadal Oscillation (PDO; Tsonis et al. 2007; Swanson and Tsonis 2009; Wang et al. 2009). The results indicate that this network in the 20th century synchronized several times. It was then found that in those cases where the synchronous state was followed by a steady increase in the coupling strength between the indices, the synchronous state was destroyed, after which a new climate state emerged. These shifts are associated with significant changes in global temperature trend over decadal time scales. We also find the evidence for such type of behavior in three climate simulations (control and CO_2 forced) using simulation from state-of-the-art models.

Part of my work was to understand relationships between regime shifts and synchronization in a set of ordinary differential equations (ODE's) representing climate modes. To this end we further studied synchronizations by extending the previous analysis to include more indices. Some results are shown in figure 1. On the x-axis are the different modes and on the y-axis is time. This figure may be interpreted as follows. Horizontal orange or yellow lines indicate synchronization events and the modes involved in each synchronization event. The main conclusion here is that de-synchronization does not always mean a regime shift. For example, while in the early 1940s a climate shift took place, no shift occurred in the 1920s or early 1930s. In accordance with the previous results only in those times when increase in coupling is involved de-synchronization is associated with a climate regime. In relation to the goals of the complete proposal it is important to establish the mechanism via which synchronization and coupling increase occur. Our results also indicate that in the four mode network the direction of influences begins with North Atlantic coupling to North Pacific which then couples to tropical Pacific which in turn couples back to North Atlantic Wang et al. 2009; Ineson and Scaife 2009).

The bulk of our knowledge about causes of twentieth century climate change comes from simulations using numerical models. A strong component in my research was the ability of models to simulate realistically the observations. In particular, these models seemingly reproduce the observed nonuniform global warming, with periods of faster warming in 1910–1940 and 1970–2000, and a pause in between. More research into to this issue (Kravtsov et al. 2014) reveals some differences between the observations and model simulations. We showed that observed multidecadal variations of surface climate exhibited a coherent global-scale signal characterized by a pair of patterns, one of which evolved in sync with multidecadal swings of the global temperature, and the other in quadrature with them. In contrast, model simulations are dominated by the stationary—single pattern—forced signal somewhat reminiscent of the observed "in-sync" pattern most pronounced in the Pacific. While simulating well the amplitude of the largest-scale—Pacific and hemispheric—multidecadal variability in surface temperature, the model underestimates variability in the North Atlantic and atmospheric indices. We also show that there exist further significant differences in the dynamics between the different models (Steinhaeuser and Tsonis 2013) especially for the surface temperature and precipitation fields; two fields of great interest in climate projections under increasing amounts of CO_2. This imposes a problem when synchronization between models is desirable.

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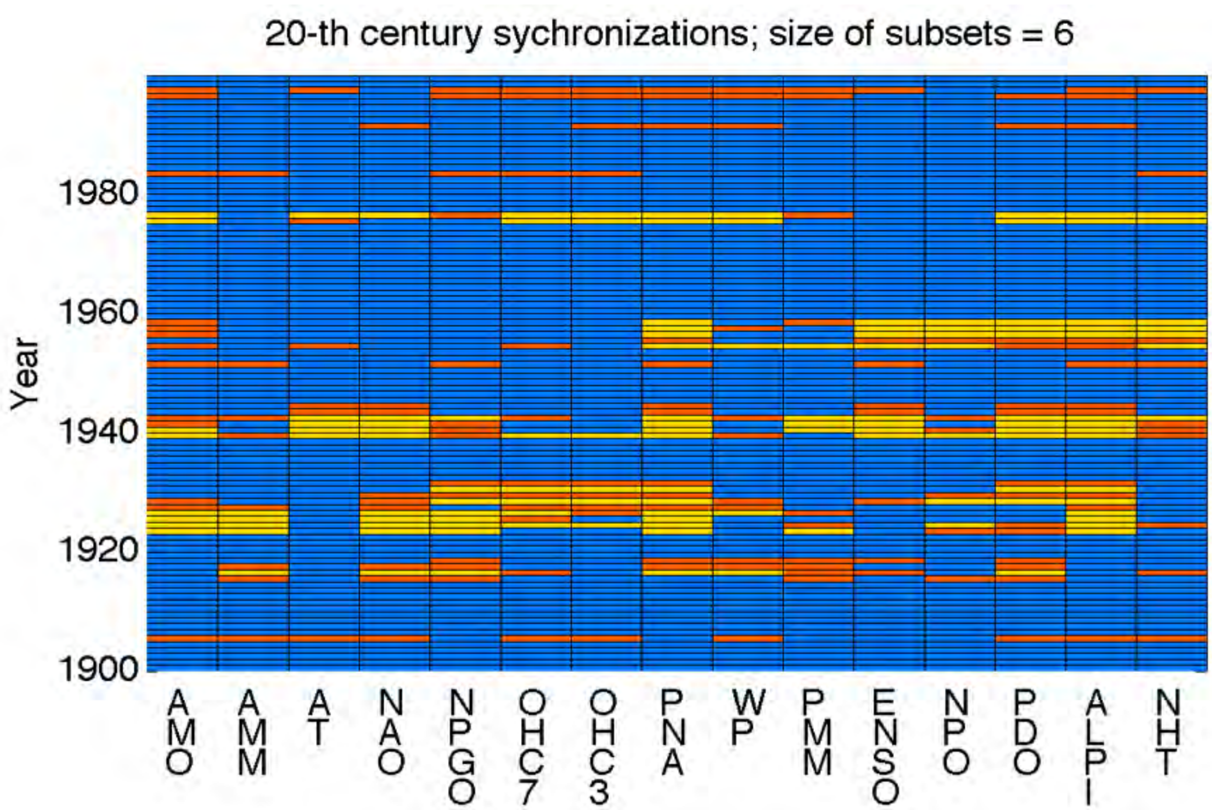

Figure 1. AMO: Atlantic Multi-decadal Oscillation, AMM: Atlantic Meridional Mode, AT: Atmospheric-mass Transfer anomalies index, NAO: North Atlantic Oscillation, NPGO: North Pacific Gyre Oscillation, OHC7: Ocean Heat Content at 700 meters index, OHC3: Ocean Heat Content at 300 meters index, PNA: Pacific North America index, WP: Western Pacific Pattern index, PMM: Pacific Meridional Mode, ENSO: El Nino/Southern Oscillation 3.4, NPO: North Pacific Oscillation, PDO: Pacific Decadal Oscillation, ALPI: Aleutian Low Pressure index, NHT: Northern Hemisphere Temperature.

Influence of the Equatorial Atlantic Cold Tongue and Angola Current on Atlantic Basin Climate Variability

PIs: E. K. Vizy and K. H. Cook
University of Texas, Austin, TX

The long term goal of this project is to utilize available high resolution NASA observations, atmospheric and oceanic reanalyses, along with a high-resolution uncoupled mixed-layer ocean model with Ekman dynamics and a coupled mixed-layer ocean/atmosphere/land surface regional climate system model to advance our understanding of the role of ocean/atmosphere interactions in the tropical and subtropical southeastern Atlantic in forcing regional and remote Atlantic climate variability. Specific objectives include a) understand the roles local and/or regional wind stress and thermodynamic processes over the southeastern Atlantic play in the development of sea surface temperature (SST) variability and coastal upwelling in the region, b) elucidate the influence of ocean/atmosphere feedback processes on regional and remote Atlantic variability of both the ocean and the atmosphere, and c) understand whether resolving small-scale oceanic structures, using a state-of-the-art coupled mixed-layer ocean/atmosphere regional climate model, can improve our predictive capabilities of the regional climate.

Research efforts in 2013 involved using available observational and reanalysis datasets to better understand decadal variations in the southeastern Atlantic climate. Our results reveal a significant warming trend in SSTs (~ over 2 K over the 32-yr period) along the Guinean and Angola/Namibian coasts and a weaker cooling trend over the sub-tropical south Atlantic (~ -0.25 K per 32-yr) over the past 32 years (1982 – 2013). These SST trends are shown to have distinct seasonality, with the most significant changes occurring during November – January. Investigation of the surface heating budget and atmospheric circulation changes during this period reveal that the austral summer SST trends are associated with a southward shift of the South Atlantic sub-tropical anticyclone as well as changes in heating over continental Africa that affect the Angola continental thermal low's position and influence the low-level circulation along the southwestern African coast. Together these atmospheric circulation changes are found to be associated with a weakening of the coastal and equatorial South Atlantic wind stress, a decrease in the coastal and equatorial upwelling, and an increase in coastal sea surface temperatures. These results are relevant for improving our understanding regional climate variability associated with global warming over this area, as the land is likely to warm faster than the ocean in the future.

Relationship of the Atlantic Warm Pool with the AMOC and Link of the AMOC with Global Climate Model Biases

PI: C. Wang
NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

This project has two major objectives. First, we examine and test a hypothesis: The Atlantic Warm Pool (AWP) plays a negative feedback role in the AMOC that acts to restore the AMOC after it is weakened or shut down. Second, we investigate common patterns of global SST biases in CMIP5 climate models which are commonly linked to the simulated AMOC.

Recent results

During the past year, we perform both diagnostic and modeling studies on the AMOC. The main findings and results are as follows:

- Our OGCM model experiments show that ocean response to the anomalous AWP-induced freshwater flux is primarily dominated by the basin-scale gyre circulation adjustments with a time scale of about two decades (Zhang et al. 2014). The positive (negative) freshwater anomaly leads to an anticyclonic (cyclonic) circulation overlapping the subtropical gyre. This strengthens (weakens) the Gulf Stream and the recirculation in the interior ocean, thus increases warm (cold) water advection to the north and decreases cold (warm) water advection to the south, producing an upper ocean temperature dipole in the midlatitude. As the freshwater (salty water) is advected to the North Atlantic deep convection region, the AMOC and its associated northward heat transport gradually decreases (increases), which in turn leads to an inter-hemispheric SST seesaw.
- Global SST biases in CMIP5 models are commonly linked to the AMOC simulations (Wang et al. 2014). We find that the cold SST bias in the North Atlantic is stronger when the AMOC is weaker, and vice versa, with an inter-model correlation of 0.85 between the SST bias and the AMOC index. The simulated SST bias in the North Pacific is linked to that in the North Atlantic. The mechanism is that the cold SST bias in the North Atlantic corresponds to a deepening of the Aleutian low and an intensification of the surface westerly winds in the North Pacific. The intensified westerly winds cool the North Pacific Ocean through enhanced latent heat flux and southward ocean advection associated with Ekman transports.

Most state-of-the-art climate models show warm SST bias in the tropical southeastern Pacific (SEP) and cold SST bias in the tropical North Atlantic (TNA). The cold SST bias in the TNA is associated with the AMOC: As the AMOC simulation is weaker, the cold SST bias in the TNA is larger. We perform coupled model experiments to show that as much as 30% of the warm SST bias in the SEP can be attributed to the cold SST bias in the TNA (Zhang et al. 2014). Our coupled model experiments also show that the cold SST bias in the TNA results in a weakening of the Hadley-type circulation from the TNA to the SEP. This meridional circulation reduces the South Pacific subtropical anticyclone and the associated subsidence, which in turn leads to a reduction of low clouds, a weakening of the easterly trade wind and thus an increase of the warm SST bias in the SEP.

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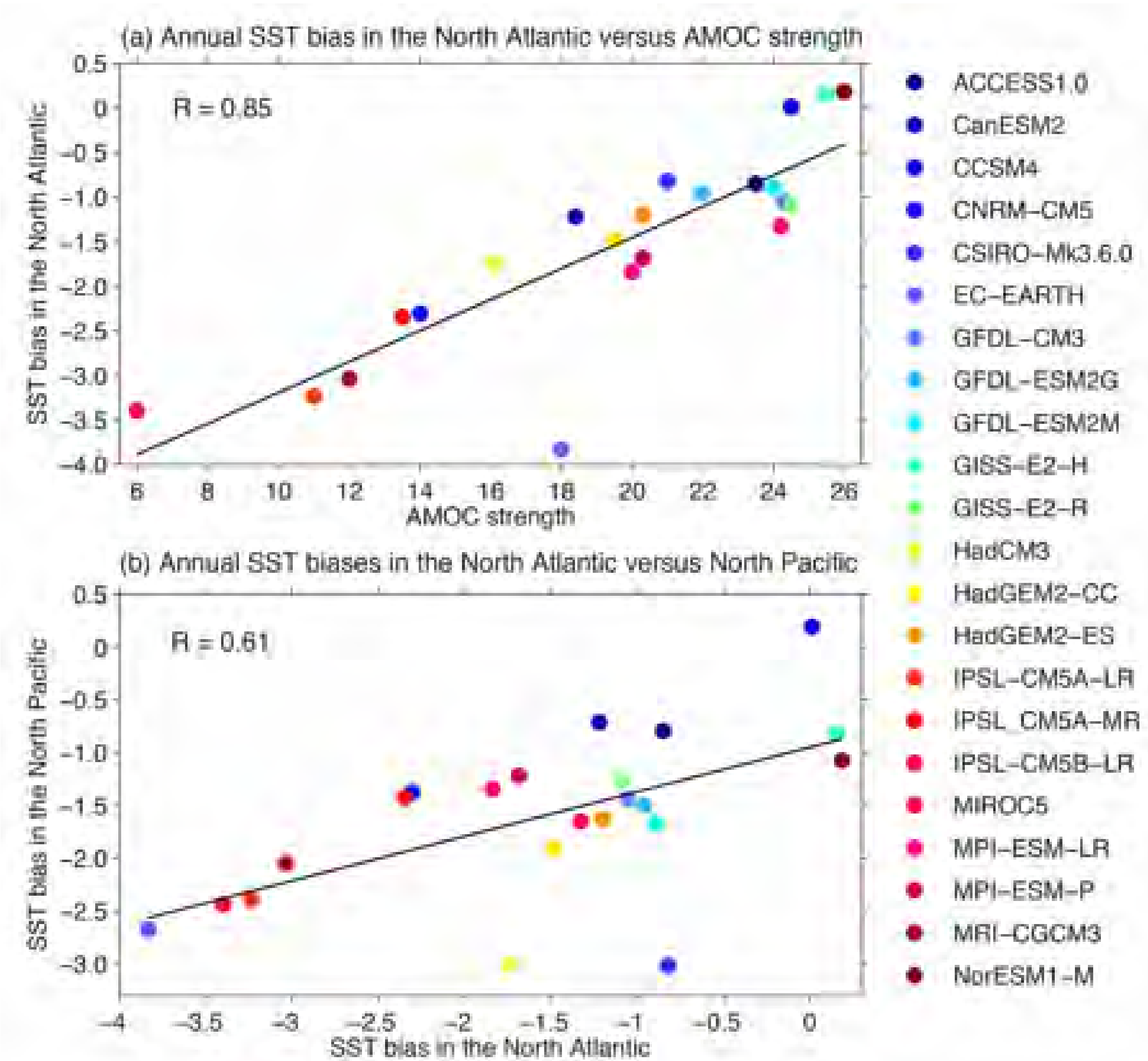

Figure 1. Relationships of SST bias in the North Atlantic with the AMOC and SST bias in the North Pacific in CMIP5 models. (a) Scatterplot of annual-mean SST (°C) bias in the North Atlantic (55°W-15°W, 25°N-50°N) versus AMOC strength (Sv) and (b) scatterplot of annual-mean SST bias in the North Pacific (150°E-140°W, 15°N-45°N) versus the annual-mean SST bias in the North Atlantic. The inter-model correlation R is shown in the left-upper side of each panel.

Satellite Multi-Sensor Studies of Deep Ocean Convection in North Atlantic Ocean

PI: X.-H. Yan[1] and Y.-H. Jo[1]
Collaborator: T. Lee[2]
[1]University of Delaware, Newark, DE
[2)]NASA Jet Propulsion Laboratory, Pasadena, CA

The objective of this project was 1) to analyze air-sea interaction and meridional heat and freshwater transport estimations to identify regions associated with preconditioning and lateral exchange prior to and post deep convection, 2) to analyze horizontal flow field and vertical water column analysis, and 3) to find linkage between deep ocean convection and subsurface thermal structure estimated from satellite multi-sensor data. The following objective was added: 4) to find the relationships of the deep convection, the AMO (Atlantic Multi-decadal Oscillation), and the AMOC together, with the slowdown of the warming in the upper layers in the central Labrador Sea as a local presentation of the current climate hiatus and their implications.

Recent results

Climate signals in the mid to high latitude North Atlantic from altimeter observations and the implications for recent global surface warming hiatus (Li et al. 2014a):

- The variability of the sea surface height anomaly (SSHA) in the mid- to high-latitude North Atlantic for the period of 1993–2010 was investigated using the ensemble empirical mode decomposition (EEMD) to identify the dominant timescales. Sea level variations in the North Atlantic subpolar gyre are dominated by the annual cycle and the long-term increasing trend. In comparison, the SSHA along the Gulf Stream is dominated by variability at intra-seasonal and annual timescales. Moreover, the sea level rise in the subpolar gyre developed at a reduced rate in the 2000's compared to rates in the 1990's, which was accompanied by rebound in SSHA variability following a period of lower variability in the system. These changes in both apparent trend and low-frequency SSHA oscillations reveal the importance of low-frequency variability in the subpolar gyre. To identify the possible contributing factors for these changes, the heat content balance (equivalent variations in the sea level) in the subpolar region was examined. The results indicate that horizontal circulations may primarily contribute to the interannual to decadal variations, while the air-sea heat flux is not negligible at annual timescale. Furthermore, the low-frequency variability in the subpolar gyre might be related to the propagation of AMOC variations from the deep-water formation region to mid-latitudes in the North Atlantic, which has the implications for recent global surface warming hiatus.

Thermal variability in the central Labrador Sea of 2003 – 2012 derived from Argo data, and a local presentation of the current climate hiatus (Li et al. 2014b):

- The dominant modes of variability in the temperature and ocean heat content (OHC; 0 ~ 1000 m) of the central Labrador Sea were investigated using the EEMD/Hilbert-Huang Transform based on Argo profiles collected during 2003-2012. Warming trends were observed in the entire water column. A strong annual cycle exists and dominates at the 500 m depth, while signals at the interannual timescales can explain most of the variability at the 1000 m and 1500 m depths. These interannual signals are closely correlated to the variability of deep convection in the Labrador Sea, which has wintertime mixed layer depth (MLD) of around 1000 m during the time period of this study with an intermittent enhancement of MLD > 1500 m. The Hilbert spectrum from the heat content (0 – 1000 m) in the Labrador Sea interior reveals two important components at periods of 0.8 ~ 1.25 years and 3 ~ 5 years, respectively, superimposed on the overall warming trends. The former corresponds to the dominant seasonal cycle due to surface heating, while the latter is concomitant with the timing of the reoccurrence of convective events. The cumulative North Atlantic Oscillation (NAO) index is significantly correlated to the low frequency variations in the heat content reconstructed from the EEMD results. Therefore, the interannual signals in the Labrador Sea, at especially the intermediate layers, are attributed to changes in the deep convective processes and the atmospheric conditions. Moreover, by comparing with an extended OHC record (1945-2010), it was also shown that the underlying warming trends from the 10-year Argo record are part of multi-decadal variations that presumably reflect the AMO. The relationships to deep convection and the AMO might, together, shed light on the slowdown of the warming in the upper layers in the central Labrador Sea as a local presentation of the current climate hiatus.

Lateral heat exchange after deep convection in the Labrador Sea (Zhang and Yan 2014):

- The mechanisms through which convected water restratifies in the Labrador Sea are still under debate. The Labrador Sea restratification after deep convection in the 2007/08 winter is studied with an eddy-resolving numerical model. The modeled mixed layer depth during wintertime resembles the Argo observed mixed layer very well, and the lateral heat flux during the subsequent restratification is in line with observations. The Irminger rings (IRs) are reproduced with fresher caps above the 300 m depths, and they are identified and tracked automatically. The model underestimates both the number of IRs in the convection area and the heat they carry. The underestimation is most likely caused by the errors in the direction of the west Greenland currents in the model, which causes more IRs propagating westward, and only the IRs originating south of 61.58N are able to propagate southward, yet with speed much slower than observed speed. The model still observed three eddies propagating into the convection area during the restratification phase in 2008, and their thermal contribution ranges from 1 to 4% if the estimation is made at the time when they enter the convection area. If all newly generated eddies are considered, then the ensemble-mean contributions by the IRs become 5.3%. The more detailed and direct heat flux by IRs is difficult to derive because of the strong fluctuation of the identified eddy radius. Nevertheless, the modeled lateral heat flux is largely composed of the boundary current eddies and convective eddies, thus it is possible for the model to maintain an acceptable thermal balance.

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Signature of the Atlantic Meridional Overturning Circulation in the North Atlantic Dynamic Sea Level

PIs: J. Yin[1], S. M. Griffies[2], S. Zhang[2]
[1]University of Arizona, Tucson AZ
[2]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

The objective of this project is to study how the Atlantic Meridional Overturning Circulation (AMOC) modifies sea level rise along the East Coast of the US and Canada, and how sea level rise patterns along this coast and in the North Atlantic can be used as an important fingerprint to detect AMOC variability and change. Recently, *in situ* observations of the AMOC reveal a 30% downturn of the AMOC during 2009-10. This event provides a valuable opportunity to study the climate impact of the AMOC, quantify the AMOC-sea level rise relationship, and test model simulation results.

Recent results

We have been focusing on the sea level signals of the 30% AMOC downturn (Goddard et al., 2015). We analyze the long-term tide gauge data along the East Coast of North America. To minimize the effect of local factors and reveal regionally coherent behavior, we calculate the time series of the sea level composite for the three sea level rise regimes: Northeast, Mid-Atlantic and Southeast. Based on the sea level composite, we identify an extreme sea level rise event during 2009-10 along the Northeast coast of North America. Within a two-year period, the coastal sea level north of New York City jumped by up to 128 mm. Despite significant year-to-year fluctuation, this magnitude of sea level rise is unprecedented (1-in-850 year event) during the entire history of the tide gauge records. We use various observational and modeling data, including those from high resolution models with an eddying ocean. We show that this extreme sea level rise event is a combined effect of two factors: an observed 30% downturn of the AMOC during 2009-10, and an onshore/alongshore wind stress anomaly associated with the significant negative North Atlantic Oscillation (NAO) index.

Significant findings

- Regression analysis indicates that for every 1 Sv of AMOC weakening, the coastal sea level north of New York City rises by 13-17 mm (Figure 1).
- Most of the state-of-the-art climate models show good correlation between the AMOC strength and the sea level rise along the Northeast coast of North America on the interannual time scale.
- The observational estimate of the AMOC-sea level rise relationship is comparable with the modeling results.
- The extreme nature of the 2009-10 sea level rise event suggests that such a significant downturn of the AMOC is very unusual.
- The negative NAO in 2010 contributed to the extreme sea level rise along the Northeast coast of North America, but is not the dominant mechanism.
- During the 21st century, most of the state-of-the-art climate models project an increase in magnitude and frequency of extreme sea level rise events on the interannual time scale along the densely populated Northeast coast of North America.

In addition, we have also contributed to the comprehensive and systematic analysis of the newly developed high-resolution models at GFDL (CM2.6 and CM2.5) (Griffies et al., 2014). The analysis foci include ocean heat transport, simulations of the AMOC and its response to future greenhouse-gas scenarios, and the sea level variability and change in the control and future projection runs.

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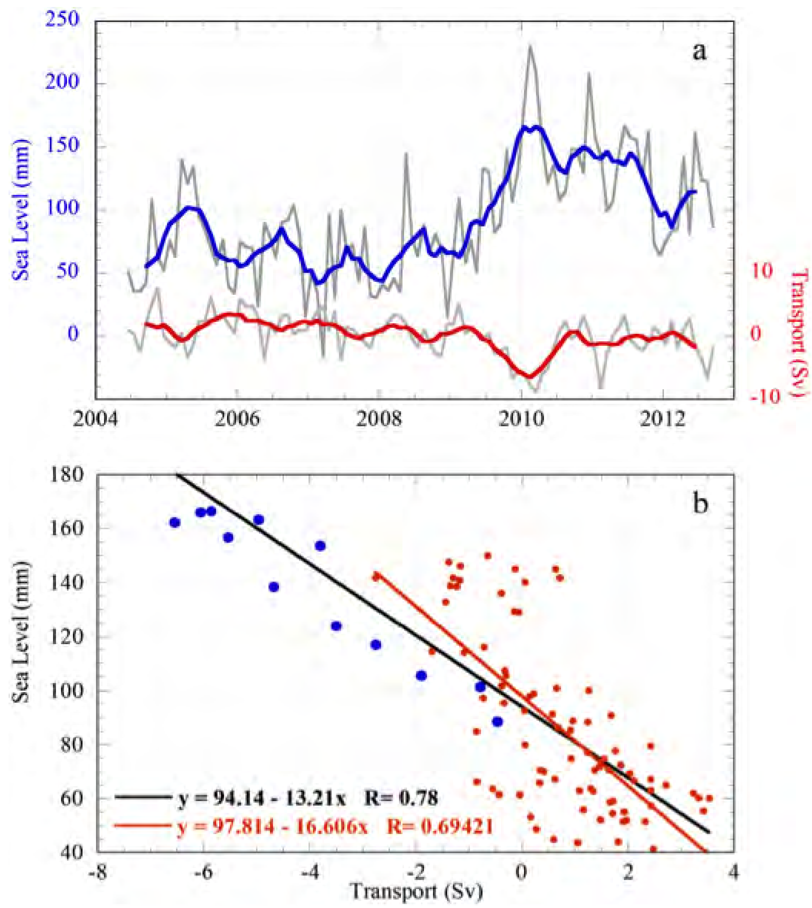

Figure 1. Correlation between the AMOC and sea level composite along the Northeast coast of North America. A) Time series of the Northeast sea level composite (gray – monthly data, blue – 6-month filtered) and the AMOC strength at 26.5°N (Sv; gray – monthly data, red – 6-month filtered). The Northeast sea level composite is calculated as the mean of 18 tide gauge stations north of New York City. b) Monthly correlation and regression between the AMOC and the Northeast sea level composite (mm Sv-1, 2-month lag with AMOC leading SLR). The blue dots highlight the data during the period of the 30% AMOC downturn. The linear fit in black is based on all monthly data during April 2004-September 2012. The linear fit line in red is based on the red dots only, which exclude the period of the 30% AMOC downtown. The data are from Permanent Service for Mean Sea Level (PSMSL) and the RAPID-WATCH MOC project sites.

Impact of AMOC on Arctic Sea Ice and Atmosphere Heat Transport into the Arctic

PI: R. Zhang
NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

The objective of this research is to understand the mechanism causing the low frequency variability of summer Arctic sea ice extent (SIE) and the implications for the observed decline trend in September Arctic SIE since 1979.

Recent results

In this study, it is shown that AMOC and the associated poleward Atlantic heat transport have played a significant role in the low frequency variability of summer Arctic SIE using the GFDL coupled climate model. At low frequency the March Barents Sea SIE anomaly is dominated by anti-correlated Atlantic inflow anomaly, thus is also significantly correlated with September Arctic SIE anomaly. The observed March Barents Sea SIE has a very similar normalized decline trends as the observed September Arctic SIE from 1979 to 2013, consistent with an increasing trend in Atlantic inflow and the multidecadal variability of AMOC implied by its fingerprints over the same period. This study estimated that a positive trend in the Atlantic inflow have contributed a substantial portion of the observed summer Arctic sea ice extent decline trend since 1979. The results also provide a clue of why most CMIP underestimate the observed summer Arctic SIE decline in recent decades, which might have been substantially affected by internal variability. If the AMOC and the associated Atlantic heat transport into the Arctic were to weaken in the near future, then there would be a slowdown in the decline trend of September Arctic SIE, and we may not have ice-free Arctic summer that soon in a few decades. This plausible scenario, with enormous social and economical impacts, cannot be ignored.

This study also shows that at low frequency, changes in poleward atmosphere heat transport across the entire Arctic Circle are compensating to and dominated by AMOC induced Atlantic heat transport anomalies into the Arctic, hence a stronger AMOC and associated enhanced Atlantic heat transport into the Arctic ocean leads to both reduced summer Arctic SIE and reduced poleward atmosphere heat transport into the Arctic. Most of the anomalous heat transported into the Arctic region by the Atlantic Ocean is released into the atmosphere, then transported southward out of the Arctic region by the anomalous atmosphere heat transport. Previous studies attribute the observed changes in the atmosphere circulation pattern and eddy heat transport in recent decades to the observed Arctic sea ice decline. However, if the recent observed Arctic sea ice decline since 1979 is also accompanied by strengthened AMOC and enhanced Atlantic Ocean heat transport into the Arctic Ocean, then changes in the atmosphere circulation pattern and eddy heat transport might have been dominated by the response to enhanced poleward Atlantic Ocean heat transport, not dominated by Arctic sea ice decline.

On the Evolution of AMOC Fingerprint in the North Atlantic

PI: R. Zhang[1]
Collaborator: J. Zhang[2]
[1]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ
[2]University of Washington, Seattle, WA

The objective of this research is to investigate the evolution of the AMOC fingerprint, its connection with the meridional coherence of AMOC variability, and the implications for decadal predictability.

Recent results

It has been revealed previously that the AMOC anomaly associated with changes in the North Atlantic Deep Water (NADW) formation has meridional coherence in density space and propagates southward with an advection speed north of 34°N due to the existence of interior pathways of NADW in this region, resulting in a several-year time lead between subpolar and subtropical AMOC variations. In this study, we found that the several-year time lead between subpolar and subtropical AMOC variations is crucial for the evolution and the enhanced decadal predictability of the AMOC fingerprint – the leading mode of upper ocean heat content in extra-tropical North Atlantic. To investigate the evolution of the AMOC fingerprint, we conducted two sets of experiments using GFDL CM2.1. The first set of experiments includes an ensemble of 10-member control experiments and an ensemble of 10-member perturbed experiments. The ensemble of perturbed experiments is initialized with the same positive salinity anomaly in upper northern North Atlantic and Nordic Sea. The initial positive salinity perturbation induces a positive AMOC anomaly at northern high latitudes, which propagates with slow advection speed north of 34°N, and with fast coastal wave speed south of 34°N. The associated Atlantic meridional heat transport (MHT) anomaly propagates in the same way as the AMOC anomaly, resulting in a convergence/divergence of the Atlantic MHT in the subpolar/Gulf Stream region respectively, thus warming (higher upper ocean heat content) in the subpolar gyre (SPG) and cooling (lower upper ocean heat content) in the Gulf Stream region after several years. Hence this distinctive dipole pattern of upper ocean heat content, i.e. the AMOC fingerprint is predictable on decadal time scale. The analysis of the GFDL CM2.1 1000-year control simulation exhibits the same mechanism for the evolution of the AMOC fingerprint.

The second set of experiments is the same as the first set except that the deep branch of AMOC in the subpolar region are fixed with time in both control and perturbed experiments, so that the AMOC anomaly cannot propagates southward through this region. There is no AMOC fingerprint developed, thus no predictable signal in the SPG and Gulf Stream region in the second set of experiments. This is because without the southward propagation of the AMOC anomaly, there is no convergence/divergence of the Atlantic MHT anomaly. The results show that the initialized subpolar salinity anomaly is important for triggering the AMOC anomaly at northern high latitudes, but itself cannot directly lead to a predictable temperature signal in the SPG and Gulf Stream region without the southward propagation of the AMOC anomaly with the slow advection speed. Recently several decadal prediction studies successfully predict the observed warm shift in the SPG in mid 1990's, and it is found that initializing a positive AMOC anomaly at northern high latitudes is the key for successful predictions. Our results here provide the physical mechanism for the enhanced decadal prediction skills in subpolar North Atlantic ocean temperature.

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US CLIVAR
Climate Variability & Predictability

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

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NASA NOAA NSF

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