U.S. CLIVAR: CLIMATE VARIABILITY AND PREDICTABILITY

FIFTH ANNUAL U.S. AMOC REPORT

U.S. AMOC: ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

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FIFTH ANNUAL PROGRESS REPORT FOR A SOST NEAR-TERM PRIORITY ASSESSING MERIDIONAL OVERTURNING CIRCULATION VARIABILITY: IMPLICATIONS FOR RAPID CLIMATE CHANGE

The U.S. AMOC Science Team

Executive Summary

The U.S. 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 U.S. 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 U.S. 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 fifth annual progress report submitted by the U.S. AMOC Science Team. The purpose of this report is to summarize progress on the main objectives of the program, identify any programmatic gaps, and make recommendations on near-term research priorities for the program.

Planning activities within the U.S. AMOC Program are organized under four "task teams" consisting of groups of program PIs, each led by a volunteer chair and vice-chair. The task teams are:

Task Team 1. AMOC Observing System Implementation and Evaluation
(Chair: Susan Lozier; Vice-chair: Patrick Heimbach)

Task Team 2. AMOC State, Variability, and Change
(Chair: Josh Willis; Vice-chair: Rong Zhang)

Task Team 3. AMOC Mechanisms and Predictability
(Chair: Gokhan Danabasoglu; Vice-chair: Young-Oh Kwon)

Task Team 4. Climate Sensitivity to AMOC: Climate/Ecosystem Impacts
(Chair: Ping Chang; Vice-chair: Yochanan Kushnir)

The task team leaders, together with the Science Team chair, form the AMOC Program Executive Committee and provide overall program guidance and liaison with the U.S. CLIVAR Office and agency program managers. Specific terms of reference describing the roles of the Task Teams in helping to coordinate research in these four areas are listed in Appendix 1, along with the current membership of each Task Team.

Meetings of the Science Team have been held annually since 2009, except during 2011 when a joint science conference was held with the U.K. RAPID-WATCH program in Bristol, England. It has been agreed that this joint meeting strategy will continue in the future, with a joint USAMOC/RAPID-WATCH science conference to be held in alternate years (the next one to be hosted by the U.S. in Baltimore, MD, in July 2013), and a national science team meeting held in intervening years.

The U.S. AMOC program has four main objectives, which are closely linked to the activities of the Task Teams:

(1) *AMOC observing system implementation and evaluation*
(2) *An assessment of AMOC state, variability, and change*
(3) *An assessment of AMOC variability mechanisms and predictability*
(4) *An assessment of the AMOC's role in global climate and ecosystems*

Progress on these four main program objectives during 2012 is summarized in section B of this report. At the 2012 annual PI meeting in Boulder, CO, each of the task teams held a half-day "mini-workshop" to explore future research directions, the results of which are described in later sections of this report. Highlights of some of the program accomplishments and emerging near-term priorities in the program are summarized below.

1. Strong efforts were put forth during 2012 toward the design of AMOC observing systems in the subpolar North Atlantic (OSNAP) and subtropical South Atlantic (SAMOC), in collaboration with international partners. Proposals were developed and submitted to funding agencies supporting the U.S. AMOC program. SAMOC has not received full support, although some elements are in place. The US OSNAP proposal anticipates a funding decision in May of 2013.

2. Observing system simulation experiments (OSSEs) using high-resolution ocean models are increasingly being used to test observing system strategies for the AMOC, notably in the above SAMOC and OSNAP program efforts, and also to assess needs for deep observations to constrain the AMOC state and variability (e.g., deep Argo). Studies based on ocean state estimates and adjoint models to understand the AMOC sensitivity to regional perturbations and key measurements that may be required in such regions to monitor and predict the AMOC state and to understand the nature of its variability are also in progress.

3. Results from several of the *in-situ* programs established as part of the AMOC monitoring network (RAPID, Line W, MOVE) are now approaching—or exceeding—a decade in length, and are becoming increasingly valuable. For example, the RAPID array has shown a significant decrease in the AMOC strength at 26.5°N during the past few years in association with a downturn in the NAO index. The ability to monitor the AMOC state and ocean heat transport using satellite and Argo data at certain latitudes where boundary transport measurements are not vital has also been demonstrated, and these methods can potentially be extended to other latitudes where boundary array measurements are available. At the same time, ocean state estimates and reanalyses are increasingly being developed and applied to study the AMOC. A high priority for the program in coming years will be to synthesize all of the results from the *in-situ* array programs and combine them with the state estimate models to develop a firm understanding of AMOC changes that are currently taking place or that have taken place in the recent past.

4. Recent studies have demonstrated that the measure of the AMOC is spatially, as well as temporally, variable. As such, there is no longer an expectation that an overturning index based on the zonally-integrated meridional flux of mass at one latitude will be coherent with that at another latitude. A near-term priority of the program is to develop a common set of metrics for the AMOC, in both depth and density spaces, that can be derived and compared between models and observations. For the convenience of multi-model comparison studies, various diagnostic variables currently not available in many climate models, such as AMOC in density coordinates needed for studying the meridional

coherence of AMOC variability, are recommended to be provided by the climate modeling centers through the CMIP data archive.

5. Model studies have suggested that there is an identifiable 'fingerprint' associated with AMOC variability, manifested in measurable broad-scale fields such as sea level and subsurface temperature patterns. Work toward developing such fingerprinting techniques to extend the AMOC record back in time using both the historical instrumental record and high-resolution paleo proxy data is continuing. A near-term priority of the program is to develop a robust multivariate fingerprint of AMOC variability based on multi-model analysis, and to explore the possibility of using long-term coastal sea level records as a proxy for AMOC variability.

6. Progress has been made in improving our understanding of AMOC variability mechanisms and of the roles of atmospheric forcing and ocean – atmosphere interactions in this variability, based on diverse approaches, including process-oriented modeling, sensitivity studies using adjoint modeling, application of transfer function approach, eddy-resolving general circulation modeling, interactive-ensemble coupled experiments, forced ocean – sea-ice hindcast simulations, and intercomparison studies of CMIP5 models and simulations. Despite progress, findings continue to be model dependent. To address this major issue, a community effort within Task Team 3 has been initiated to perform coordinated and focused experiments across a hierarchy of approaches to further our understanding of AMOC mechanisms, using a common set of metrics.

7. AMOC prediction and predictability continue to be a main focus of the major climate modeling centers. Results from ensemble decadal prediction experiments continue to show measurable skill in predicting AMOC and heat content anomalies in the North Atlantic, with some suggesting potential predictability up to a decade in advance, while others show more limited predictive skill. Further effort needs to be directed toward assessing the robustness and model dependency of the predictions, and to determine the best practices for model initialization and model bias correction. These efforts can be advanced through focused inter-comparisons of the existing IPCC AR5 decadal prediction experiments, complemented by additional, coordinated verification studies where the U.S. AMOC program can play a coordinating role.

8. Much more research has been accomplished linking global climate and precipitation variability to changes in the AMO/AMV SST patterns in the Atlantic. The widespread impacts of AMV are being clearly elucidated by U.S. AMOC investigators and other researchers, but further study is needed to understand the physical linkages between AMOC variability and SST variability over the Atlantic, especially the connection between the AMOC and AMV. In addition, the U.S. AMOC program is trying to expand its scope of AMOC impact studies to problems involving sea level, sea ice, ocean ecosystems, and carbon uptake, by recruiting new PIs who are active in these areas and by building bridges to other programs with mutual research interests.

9. Elements of the AMOC have been recognized by the U.S. CLIVAR Working Group on Greenland Ice Sheet-Ocean Interactions (GRISO) to play a potentially important role in contributing to the recent speedup of Greenland's marine-terminating outlet glaciers, notably through changes in the circulation in the subpolar gyre and associated increased penetration of Atlantic waters into Greenland's fjords. The GRISO WG has identified this issue as an important topic for further focused research.

Finally, a strong recommendation coming out of discussions at the 2012 annual PI meeting is that the U.S. AMOC Program and supporting agencies should seek to fully exploit the synergy of the AMOC Science Team. The 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 be strongly encouraged and supported.

Fifth Annual Progress Report for a SOST Near-Term Priority Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change

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Fifth Annual Progress Report for a SOST Near-Term Priority Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change

A. INTRODUCTION

In January 2007, 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 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 inter-agency 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 U.S. 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 all PIs designated by the funding agencies to be performing research relevant to the U.S. AMOC program, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies. As part of this responsibility, the Science Team produces annual progress reports that are intended to 1) facilitate the dissemination of recent research results, 2) help the agencies as well as the scientific community identify gaps in our understanding and measurement of the AMOC, and 3) aid the coordination of efforts across agencies. A further goal of the progress reports is to provide concise and timely communication to international collaborators on the U.S. AMOC efforts, including the identification of evolving science and monitoring issues.

The report herein is the fifth annual progress report submitted by the U.S. AMOC Science Team. This report describes the progress made in the four major areas of focus within the program, followed by an identification of high priority, near-term research objectives.

B. PROGRESS ON PROGRAM OBJECTIVES

1. AMOC observing system implementation and evaluation

1.1 Existing observational programs

All components of the *in-situ* observational component of the U.S. AMOC program detailed in the 2011 U.S. AMOC Report have continued to measure elements of the Atlantic Ocean circulation. They comprise:

- the joint U.K.-U.S. RAPID-MOCHA (Rapid Climate Change – Meridional Overturning Circulation and Heat flux Array) program along 26.5°N with two specific US responsibilities:
  - a Florida Straits measurement effort and a western-Atlantic contribution to RAPID led by *Baringer, Meinen and Garzoli*

  - an estimation effort of meridional heat transports in the subtropics based on the RAPID array, led by *Johns, Beal, Meinen and Baringer*
- a sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39°N (Line W) led by *Toole, McCartney, Curry, Joyce and Smethie,*
- sustained observations of ocean currents in the NW Atlantic between New York and Bermuda based on hull-mounted ADCP measurements from the container vessel *CMV Oleander*, led by *Donohue, Flagg, and Rossby*
- the Meridional Overturning Variability Experiment (MOVE) along 16°N, led by *Send and Lankhorst*)
- the Southwest Atlantic MOC project (SAM) led by *Meinen, Garzoli, Baringer, and Goni*
- the Davis Strait project, led by *Lee, Gobat, Stafford and Moritz*

Each of these components are described in more detail in the 2011 US AMOC Report. We limit discussion here to new findings obtained during the last year.

Overarching themes of the scientific analyses were quantification of observed variability derived from the available observations, investigation of the physical mechanisms, processes and forcings causing the observed fluctuations, and potential impacts.

Significant attention has remained on the 26.5°N section where the RAPID-MOCHA array exists. Updated time series of volume transport estimates derived from the array are shown in the MOCHA project report in Appendix 4 (from McCarthy et al. 2012), as well as in the forthcoming NOAA State of the Climate 2012 report (Baringer et al. 2013). They exhibit, in addition to the pronounced seasonal variability reported earlier, signs of marked inter-annual variations, with annual means varying from 18.7 ± 0.5 Sv to ~15.0 Sv. A marked reduction of monthly MOC values during the winter 2009/10 and again in 2010/11 is the subject of intense interest (e.g., Srokosz et al. 2012), but its cause is not fully understood. While part of the reduction appears to be related to reduced Ekman transport associated with the extreme low NAO phase over the North Atlantic, mid-ocean geostrophic transports, as well as changes in the western boundary current also contribute significantly. Heat transport estimates derived from the RAPID-MOCHA time series range from annual means of 1.1 to 1.3 PW over the period 2004 to 2010. Ocean heat content in the subtropical gyre north of the RAPID line shows a marked decrease in late 2009, coincident with the downturn in heat transport across 26.5°N.

An increased focus has been placed on the variability of the deep western boundary current (DWBC) at various latitudes. In particular, it was found that the DWBC is highly variable at 34.5°S (Meinen et al. 2012), with variations of 40+ Sv occurring over a few days and transport anomalies of 20+ Sv persisting for months. This finding appears at odds with the traditional view that only part of the deep limb of the MOC would flow along the western boundary at 34.5°S, with the rest believed to be flowing southward along the western continental slope of Africa. Model-based estimates of the time it would take for an observing system in the SAM location to capture the full range of DWBC variance place a lower bound at ~5 years.

Analyses of data from Line W at 39°N continued to establish water mass properties in the DWBC in terms of subpolar origin and associated remote forcings (Peña-Molino et al. 2011, 2012). The time series now extends the one presented by Toole et al. (2011) to include the 2008-2010 period. It too reflects large short frequency variability, with intermittent pulses in excess of three times the mean transport values due to intermediate and deep water variability.

Measurements of Gulf Stream variability are obtained especially from Line W (Toole et al. 2011) and the Oleander Project (Rossby et al. 2010). Both projects have provided detailed process studies of eddy propagation (Rossby et al. 2011; Joyce et al. 2013) and Gulf Stream meandering on monthly to inter-annual time scales (Curry et al. 2011). Joint analyses were performed to relate Line W measurements to satellite altimetric data as well as bottom pressure recording, with a goal of exploring the possibility to extend the Line W-derived transport time series back in time (e.g., Brearley et al. 2013) or to basin-wide transport estimates (Elipot et al. 2013).

Online Resources

ECCO: http://ecco-group.org
Line W: http://www.whoi.edu/science/PO/linew/index.htm
MOCHA: http://www.rsmas.miami.edu/users/mocha
RAPID: http://www.noc.soton.ac.uk/rapidmoc
SAM: http://www.aoml.noaa.gov/phod/research/moc/samoc/sam/

1.2 Enhancements to the AMOC Observing System

Two internationally-coordinated programs, the South Atlantic Meridional Overturning Circulation (SAMOC) and the Overturning in the Subpolar North Atlantic Program (OSNAP), both described below, are planned enhancements to the AMOC observing system.

An operational pilot program at 34.5°S serves as the beginning of a planned international program for the measurement of the full-water-column, full-basin, meridional velocity, along with temperature and salinity in the South Atlantic. Selected near-shore/continental shelf components are already funded and in the water, as is a pilot array studying the western boundary components of the MOC at 34.5°S. The first International SAMOC cruise took place on board the Brazilian research vessel N.Oc Alpha Crusis in November/December of 2012, with participation of scientists from Argentina, Brazil and the US. The cruise was in support of the NOAA Southwest Atlantic MOC project ("SAM") and the broader international SAMOC initiative to monitor the MOC and the MHT across 34.5°S.

Work towards the goal of implementing an observing system that will capture the MOC in the subpolar North Atlantic culminated in the submission of a proposal to NSF in August, 2012. OSNAP (Overturning in the Subpolar North Atlantic), a U.S.-led international program, is designed to provide a continuous record of the full-water column, trans-basin fluxes of heat, mass and fresh water in the subpolar North Atlantic. The proposed observing system consists of two transects: 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 southeast tip of Greenland to Scotland (OSNAP East). The location of the two transects melds nicely 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 OOI node to be placed in the southwest Irminger Sea; the repeat A1E/AR7E hydrographic sections across the Irminger and Iceland basins; and the ongoing Ellet line in the Rockall region. Additionally, the observing system includes subsurface floats to trace the pathways of overflow waters in the basin. Substantial international collaboration has been garnered, including measurement contributions from the U.K., Germany, the Netherlands and Canada. Importantly, this proposed observing system, in conjunction with the RAPID/MOCHA array at 26°N and the EU NACLIM program, will provide a comprehensive measure of the meridional overturning circulation in the North Atlantic and provide a means to evaluate inter-gyre connectivity.

2. An assessment of AMOC state, variability, and change

The U.S. AMOC program supports a variety of efforts designed to assess the physical state of the AMOC, that is, the rates of volume and heat transport carried by the AMOC. This includes work to assess the relationship between AMOC variability and other observable quantities, often referred to as AMOC fingerprints. A variety of tools are used to make these assessments, including observations, ocean simulations, coupled climate simulations and data assimilation efforts. Here we describe progress on these efforts as they pertain to the near-term research priorities described in section C.

2.1 Observational results

The Charlie-Gibbs Fracture Zone (CGFZ) is an important gateway for both the warm and cold limbs of the AMOC across the Mid-Atlantic Ridge. *Bower and Spall* deployed an array of 8 current meters in August 2010 to measure currents and water properties between the bottom and 500 meters. The array, deployed in collaboration with Dr. Monika Rhein (University of Bremen), is designed to begin long-term observations of both the westward and eastward flows over the CGFZ as well as diapycnal mixing there. The moorings were recovered in July 2012 and data processing is under way. *Bower and Spall* also maintain a modeling effort focused on the complex circulation in the CGFZ.

The slowdown of the subpolar gyre in the North Atlantic has been well documented in previous works by *Rhines and Häkkinen*. In their latest effort, they update the ongoing slowdown of the gyre and diagnose its relationship to heat content and SSH in the gyre. They note a further, sudden slowdown in 2010 that corresponded to the sudden drop in the AMOC observed at the RAPID array. In addition, they have described an association between a warm subpolar North Atlantic and the frequency of atmospheric blocking patterns in the Atlantic storm track.

One of the primary reasons for investigation of the AMOC is its role in the northward transport of heat throughout the Altantic Ocean. *Kelly and Thompson* investigated northward heat transport in the Atlantic using a variety of observations including altimetry as well as a variety of different models. They found a high degree of meridional coherence from 30°S to 40°N, and showed that upper-ocean heat transport convergence drives the heat budget in both the Gulf Stream and North Atlantic Current, and are currently investigating regions in the North Atlantic where upper ocean heat content changes lead heat flux anomalies to the atmosphere by 3 to 4 months.

In the South Atlantic, connection between the strength of the North Brazil Current (NBC) and deep convection in the Labrador Sea is being explored by *McPhaden, Zhang and Cheng*. Decadal upper ocean salinity anomalies in the western tropical and subtropical Atlantic thermocline are correlated with the NBC (and AMOC) transport, and these transport anomalies lead salinity anomalies in the eastern subpolar gyre by 5-8 years, suggesting that much of the recently observed salinification in the eastern subpolar gyre is a result of the AMOC variation. In addition, NBC variability has been connected to changes in AMOC transport using forced ocean models as well as coupled climate models.

Efforts to identify AMOC-related signals in satellite observations such as sea surface temperature, sea surface height, and surface wind speed remain important research priorities because they provide insight into the connection between AMOC variability and its impact on climate. *Minnett and Gentemann* found that AMOC variability as measured by the RAPID array at 26.5°N corresponds well with changes in the SST averaged over the subpolar North Atlantic. Although this effort has now come to an end, a manuscript is in preparation on this result.

Shum, Kuo and Yi continue their efforts to estimate AMOC variability using satellite observations of sea surface height and gravity along with hydrographic observations. Time varying estimates of surface currents based on these observations show the evolution of the subtropical and subpolar gyres.

Yan and Jo used satellite altimeter observations of sea surface height to investigate sea level trends in the subpolar and subtropical gyre as well as interannual variability in the subpolar gyre and Gulf Stream regions. Their results indicate that the low frequency variability in the subpolar gyre might be related to the deep ocean convection process and the propagation of the AMOC variations between high- and mid-latitudes.

The Iceland-Scotland Overflow Water, or Northeast Atlantic Deep Water supplies approximately 1/3 of the North Atlantic Deep water, which is the major artery of the deep limb of the AMOC. *Rhines and Eriksen* analyzed almost 19,000 hydrographic profiles and other physical and biological observations from Seagliders that sample the Iceland-Faroe Ridge. The glider data were used to determine dissipation and mixing and the observations showed that the dense water does not break into isolated boluses as it flows downslope, as is often the case in simulations.

Freshwater export from the Hudson Strait is the third largest oceanic contributor of freshwater to the North Atlantic. *Straeno and Lentz* are carrying out an effort to quantify the variability of this freshwater export and understand the processes that regulate it using moored data and models. Recent papers have shown that freshwater export is dominated by regional wind forcing on interannual time scales and by the river input variability on longer time scales.

Transformation of Atlantic Water in the Lofoten Basin dominates much of the warm to cold conversion occurring in the Nordic Seas. *Straneo, Spall, Rossby and Lilly* are investigating this element of the AMOC using a series of RAFOS floats and profiling moorings deployed in June 2010. Analysis of data from the moorings is underway, but preliminary results confirm the importance of eddies in fluxing warm, salty Atlantic waters from the boundary while continuously re-stratifying the basin.

Willis and Hobbs used a combination of satellite sea surface height observations and Argo measurements of temperature, salinity and mid-depth circulation to estimate the overturning circulation and the ocean heat transport at 41°N (Hobbs and Willis 2012) and their variability from 2002 to the present. In the final year of this project, estimates of overturning variability and heat transport variability were updated and a preliminary effort to investigate freshwater convergence between 41°N and 26.5°N was carried out. Future updates of the ocean heat and volume transports will be carried out under a ROSES grant focused on ocean surface salinity.

2.2 Data assimilation models and synthesis

Rhines and Häkkinen supported the completion of a Ph.D. Dissertation by H. Langehaug of Univ. of Bergen investigating watermass transformation in the subpolar mode water of the Atlantic as represented in three coupled climate models. Langehaug established a connection between watermass formation and decadal variability in all models, which followed changes in the AMOC in two of the models.

Using a high-resolution regional model, *Yan and Jo* investigated deep convection and subsequent restratification in the Labrador Sea. Results suggested that boundary current eddies play an important role in restratification while Irminger Rings - eddies shed from the boundary current along the west coast of Greenland - maintain strong stratificaion around the boundary current area.

Carton continued to investigate decadal variability in the Nordic and Arctic Seas and their link to NAO forcing using the Simple Ocean Data Assimilation (SODA) model. Heat budget calculations based on SODA suggest that advection of heat from the subtropics into the polar region may provide a link between subtropical surface temperature anomalies and heat content changes in the polar seas.

Ocean state estimation efforts led by *Wunsch, Heimbach and Ponte* are ongoing. Wunsch and Heimbach (2013a) describe a new-generation ocean state estimate from the ECCO project, which provides a two-decade context for the inter-annual variability inferred from RAPID at 26°N. The meridional heat transport derived from ECCO estimate for the period 1992 to 2010 is ~1 ± 0.3 PW, with standard deviations being based on monthly values and constituting a lower bound of expected uncertainties. Their results suggest the AMOC to describe a stochastic integration process of random fluctuations with little meridional co-variability or spectral coherence, and that a simple AMOC index at any one latitude is of limited use for mechanic understanding. Many processes, including a very strong annual cycle, inferred mixing coefficients, and assumptions about space/time correlations, influence estimates of AMOC changes and potential predictability. Some linear predictive skill does exist, as a function of latitude, for the AMOC, but limited to well below a decade (Wunsch, 2012; Zanna et al., 2012). Additional findings of the work relate to the impact of ocean surface advection processes in the evolution of sea surface temperature at seasonal and interannual timescales -relative to other factors such as mixing and surface heat exchange - and an assessment of currently unobserved deep ocean variability and its potential impact on estimates of sea level, heat content and other quantities related to changes in the AMOC (Ponte 2011, 2012; Piecuch and Ponte 2011, 2012; Wunsch and Heimbach 2013b).

3. An assessment of AMOC variability mechanisms and predictability

During the past year, progress has been primarily in improving our understanding of AMOC variability mechanisms and of the roles of the atmospheric forcing and ocean – atmosphere interactions in this variability under present-day, future, and paleo climate settings. As in the past, approaches have been diverse, ranging from theoretical and idealized model studies to ocean – sea-ice coupled models to complex, state-of-the-science coupled earth system models, at various resolutions.

AMOC mean, variability, and trends simulated by various fully coupled models that participate in the Coupled Model Inter-comparison Project phase 5 (CMIP5) and by forced ocean – sea-ice models were studied further by *Cheng and Zhang*. Cheng et al. (2013) have examined the AMOC in historical (1850-2005) and future scenario experiments. Although models exhibit considerable differences in details of AMOC variability and trends, the 20th century simulations show a small weakening trend for AMOC, accompanied by a multi-decadal variability with a period of about 60 years in the multi-model ensemble mean. The RCP4.5 and RCP8.5 scenarios have a weakening AMOC, but while the AMOC shows slow and steady recovery in RCP4.5 near the end of the 21st century, it continues to decline in RCP8.5.

In previous analysis of AMOC variability in fully coupled NCAR CCSM3 and CCSM4 simulations, the AMOC was calculated using depth as vertical coordinate (Kwon and Frankignoul 2012; Danabasoglu et al. 2012). To complement this analysis, *Kwon, Frankignoul and Danabasoglu* have recently reconstructed the CCSM3 and CCSM4 AMOC based on density as the vertical coordinate. The meridional coherences of the AMOC decadal variability based on the two different coordinates exhibit a significant contrast in the subpolar latitudes. While the density-based AMOC better represents the contribution from the subpolar gyre circulation and shows northward propagation of the AMOC anomalies carried by the gyre circulation, the depth-based AMOC emphasizes the deep circulation and exhibits southward propagation of the AMOC in subpolar latitudes. Further progress has been made in understanding AMOC behavior in CCSM3 where very regular and strong decadal AMOC variability is followed by a red noise-like AMOC regime with irregular and weak multi-decadal variability. Increasing density in the deep ocean below 2000 m appears to result in changes in the Labrador Sea convection and subpolar gyre circulation, leading to changes in AMOC variability behavior.

Delworth and Rosati have examined AMOC characteristics in a new generation of high-resolution coupled climate models developed at GFDL (Delworth et al, 2012). These models have ocean resolution that can be characterized as either eddy-permitting or eddy-resolving. This is complementary to analyses of AMOC variability in the GFDL CM2.1 model, which shows pronounced interdecadal and multi-centennial timescales of AMOC variability.

Danabasoglu and collaborators have started analysis of the AMOC mean state and variability in a set of 18 ocean – sea-ice hindcast simulations from an internationally coordinated effort. These simulations are forced with the inter-annually varying Coordinated Ocean – ice Reference Experiments atmospheric data sets (CORE-II) for the 60-year period from 1948 to 2007. Preliminary results show that the models that are able to simulate deep convection in the Labrador Sea have a dominant AMOC variability pattern associated with a large-scale spin-up of AMOC between about 1970 and 2000. There is a similar agreement on driving mechanism, with most models showing enhanced deep convection in the Labrador Sea that precedes the decadal AMOC changes. This multi-model result suggests that the source of the significant North Atlantic prediction skill in some decadal prediction systems, e.g., in that of NCAR (Yeager et al. 2012), comes from accurate initialization of a slow spin-up of AMOC, which occurred over the latter half of the 20th century.

Fedorov and Sévellec have worked on a generalized stability analysis that uses tangent linear models in conjunction with their adjoints to determine a variety of characteristics of AMOC, including its stability. They have applied this method to the NEMO-OPA model solutions to show rigorously the existence of a weakly-damped mode of oscillation centered in the North Atlantic (Sévellec and Fedorov 2013a). This mode was related to the dynamics of the AMOC. *Federov and Sévellec* also formulated an idealized model to highlight the importance of the strong background meridional temperature gradient for the oscillatory mechanism of this mode. Furthermore, they looked into the most efficient way to excite this inter-decadal AMOC mode and found it to be via optimal initial perturbations in surface temperature and salinity centered off the east coast of Greenland and Canada, south of the Denmark Strait (Sévellec and Fedorov 2013b).

A similar approach was conducted by *Zanna, Heimbach* and collaborators (Zanna et al., 2012) who computed optimal perturbation pattern corresponding to transient amplifications of AMOC and SST norms in the Atlantic. Solving a generalized eigenvalue problem, involving tangent linear and adjoint versions of the MITgcm, they showed that whereas time scales for optimal upper ocean perturbations reached roughly two decades, efficient perturbation of the AMOC could be achieved within roughly 7 years, implying predictability to be limited to less than a decade.

As in previous years, assessments of various aspects of simulated AMOC and meridional heat transport (MHT) against available observations continued. *Dong, Goni, Baringer and Halliwell* found that the IPCC-AR4 models are unable to capture the mean and variability of the observed boundary currents in the South Atlantic, particularly along the eastern boundary, resulting in differences from observational estimates of the AMOC and MHT at 34°S (Dong et al. 2011). In another comparison study, *Dong* and collaborators showed differences in AMOCs diagnosed from temperature and salinity fields from Argo floats and from a GFDL simulation. Although the model mean interior transports are larger than in observationally-based estimates, the model geostrophic component has a much weaker seasonal cycle than suggested by the observations. These differences are attributed to model density biases and biases in model wind stress curl, respectively.

Atmospheric forcing associated with AMOC has continued to be the focus of several studies to understand the mean and variability of the AMOC. Conducting a set of interactive-ensemble simulations with CCSM3 and a set of CORE-II forced ocean – sea-ice experiments, *Chang and Kirtman* showed that internally generated high-frequency, synoptic-scale weather variability in the atmosphere plays a significant role in maintaining the overall strength and variability of AMOC (Wan et al. 2013). They speculate that the intensified Atlantic storm track activity during the 20th century may have exerted a strong influence on AMOC's long-term trend variability by counteracting the effect due to subpolar ocean surface buoyancy increase in response to global warming.

Yeager and Danabasoglu examined the relative importance of atmospheric momentum vs. buoyancy forcing in driving the long-term AMOC changes in CORE-II forced ocean – sea-ice coupled simulations (Yeager and Danabasoglu 2013). This analysis shows that the upward trend in AMOC transport during the latter half of the 20th century is predominately driven by buoyancy forcing, while momentum fluxes contribute primarily to inter-annual and high frequency fluctuations of the AMOC. The buoyancy-driven decadal AMOC changes apparently emanate from the Labrador Sea and subsequently propagate southwards. The genesis of these anomalies in the high latitudes coincides with extreme outbreaks of cold and dry air, consistent with the *Chang and Kirtman* study.

During previous years, *McCreary* and co-workers studied key processes driving AMOC using an idealized model forced only by a surface buoyancy flux (Schloesser et al. 2012). This study has been recently extended to include forcing by a zonal wind stress. Their results show that solutions forced by both zonal wind stress and buoyancy fluxes differ markedly from those forced only by buoyancy fluxes.

Tziperman and collaborators (MacMartin et al. 2013) used transfer functions to estimate the frequency-dependent and model-dependent characteristics of specific processes involved in the AMOC. Specifically, they investigated the response of AMOC strength to surface forcing in eight models from CMIP3 and CMIP5. Transfer functions were evaluated from surface temperature, salinity, and wind stress, to the AMOC strength. They find very little agreement between models for any of the pairs of variables considered, suggesting the existence of systematic model errors, and that considerable uncertainty in the simulation of AMOC in current climate models remains. Nevertheless, a robust feature is that models with spectral peaks in their AMOC correspond to those in which AMOC variability is more strongly excited by high-latitude surface perturbations that have periods corresponding to the frequency of the spectral peaks.

The role of freshwater fluxes on AMOC behavior has been the focus of several studies. In particular, two projects have used eddy-resolving ocean models to understand the impact of glacier melting, especially in the paleo-climate context. To more accurately simulate the delivery of freshwater from the major continental ice sheets of Greenland and Antarctica to the open ocean convection regions during both glacial and modern-day periods, *Condron and Bradley* have continued to develop a state-of-the-art thermodynamic iceberg model. The model incorporates the most recent advances in iceberg physics and considers grounding, iceberg stability, surface albedo changes, collisions, and calving. Preliminary results are very encouraging. They also developed a high resolution North Atlantic – Arctic regional ocean – sea-ice model to investigate specifically the impacts of freshwater released from icebergs during the

Last Glacial Maximum. An early finding indicates that icebergs are primarily confined to the coastal boundary currents of the subpolar North Atlantic when the ocean is simulated at high resolution with very little penetration of icebergs into the central Greenland and Labrador Seas.

Weijer and collaborators compared the response of AMOC to anomalous freshwater input from the Greenland Ice Sheet in both eddy resolving and non-eddy resolving ocean model simulations (Weijer et al. 2012). They find both quantitative and qualitative differences in the AMOC response. While the coarse resolution model displayed a rapid decline (order several years) in AMOC strength which leveled off quickly, the high resolution solutions had a more gradual decline in AMOC on decadal time scales and eventually the AMOC was weaker than in the coarse resolution model. These comparisons and additional experiments with different perturbation freshwater flux distributions suggest that explicitly resolving the mesoscale eddy field and applying Greenland Ice Sheet melt with a realistic spatial distribution are important for a correct AMOC response to surface freshening of the subpolar North Atlantic.

In further ongoing work, *Kim* has been developing tangent linear and adjoint versions of the Parallel Ocean Program (POP) model to directly calculate freshwater forcings that create the largest change in AMOC and affect its stability.

Hu and collaborators examined AMOC characteristics also in a paleo-climate change context. In this project, the impact of the Bering Strait througflow on the AMOC hysteresis and global climate under glacial and interglacial climate conditions was studied (Hu et al. 2012a; 2012b). Closing the Bering Strait and preventing its throughflow between the Pacific and Arctic Oceans during the glacial period in CCSM simulations leads to the emergence of stronger hysteresis behavior of the ocean conveyor belt circulation and creates conditions that are conducive to triggering abrupt climate transitions. They argue that because the Bering Strait is open at present, abrupt climate transitions similar to those in the last glacial time are unlikely, even under greenhouse warming. Using the same coupled model, they further show that the Pacific-Atlantic seesaw-like climate change associated with changes of the AMOC can only occur when the Bering Strait is closed.

In addition to atmospheric and freshwater forcing, the impacts of the Antarctic Circumpolar Current (ACC) and Nordic Sea overflows on AMOC were also examined in several projects. Using a combination of IPCC AR4 numerical simulations and idealized models, *Kamenkovich and Radko* have continued their analysis of the relationships between air-sea density fluxes and isopycnal AMOC, considering the concept of the push-pull mode, which represents the combined effects of the adiabatic forcing in the North Atlantic and ACC in the Southern Ocean (Han et al. 2013). Surface signatures of recent climate changes in the ACC region and mechanisms that control these changes have also been examined. The results suggest that the combination of the cooling effect of intensifying winds and the opposing effects of strengthening eddies must be accounted for when estimating the response of the ACC stratification and related AMOC variability to changes in climate (Kravtsov et al. 2011).

The Nordic Sea overflows, i.e., Denmark Strait and Faroe Bank Channel, represent important components of the lower limb of AMOC. An overflow parameterization based on the Marginal Sea Boundary Condition (MSBC) scheme of Price and Yang (1999) is used in the CESM ocean component to represent the unresolved effects of these overflows. *Yang* and collaborators have begun to work on improving the MSBC scheme to incorporate progress made in the understanding of overflow physics over the last 15 years. Determination of upstream conditions, entrainment parameterization, and impacts of mesoscale eddies on entrainment and descent are being revisited.

Mechanisms by which the AMOC impacts atmospheric and sea-surface temperature variability were also examined as part of AMOC mechanism studies. The atmospheric response to steady and strong Nordic Sea overflows has been examined using the GFDL CM2.5 high resolution coupled model by *Zhang* and collaborators. Comparing results of a perturbation experiment in which a steady and strong Nordic Sea overflow is maintained, relative to a control case with a very weak overflow, they find that a stronger and deeper-penetrating Nordic Sea overflow leads to warmer SST east of Newfoundland and colder SST south of the Grand Banks, i.e., a dipole SST anomaly. This SST structure excites an atmospheric sea level pressure response with subsequent changes in precipitation, evaporation, surface heat fluxes, and low cloud liquid water content.

Kwon and collaborators have also examined atmospheric responses to differences in AMOC variability between the two distinct multi-decadal AMOC regimes in CCSM3, based on maximum covariance analysis (Frankignoul et al. 2013). A weak negative NAO-like atmospheric response was found in the strong oscillatory regime, while a more robust positive NAO-like response was detected in the red noise-like regime, but the responses were strongly dependent on the season.

Motivated by the conclusion of Booth et al. (2012), which implicated aerosols as a prime driver of the 20th century North Atlantic climate variability, *Zhang* and collaborators analyzed the HadGEM2-ES all-forcing historical ensemble simulations and showed that there are important discrepancies between the HadGEM2-ES simulations and observations, casting some doubt on the main conclusion of Booth et al. (2012). Zhang indicates that the observed AMV is more consistent with the mechanism associated with AMOC variability.

The prediction and predictability of AMOC continue to be explored using the GFDL and NCAR models, led by *Delworth and Rosati* at GFDL and *Danabasoglu, Tribbia, and Karspeck* at NCAR. An extensive suite of decadal-scale hindcasts has been completed at GFDL, using the GFDL CM2.1 coupled climate model (Rosati et al, submitted). Specifically, for each year from 1961-2012, a ten-member ensemble of decadal-scale predictions was initiated on 1 January of each year. For these experiments the model was initialized with observations based on January 1 of that year, and each ensemble member was integrated forward in time for 10 years. In addition, a ten-member ensemble of experiments was conducted with the same model but without initialization of the model with observations, to study the impacts of initialization on decadal predictive skill. Analysis of these experiments shows that on decadal time scales most of the predictive skill for near-surface temperatures is associated with radiative forcing changes. However, for the North Atlantic there is an additional source of predictive skill that comes from model initialization associated with aspects of AMV and ocean circulation changes related to the AMOC (Yang et al. 2013; Msadek et al. in press), consistent with findings of Yeager et al. (2012). Using a technique that extracts the most predictable pattern, the model shows some predictive skill for a pattern of North Atlantic SST anomalies, with the dynamical model showing more skill than persistence for lead times up to 7 years. At NCAR, efforts were focused primarily on documentation of the ocean data assimilation system, work on further improvements of the decadal prediction framework, and investigation of bias correction techniques and of impacts of ocean initialization.

4. An assessment of AMOC's role in the global climate

AMOC variability has been invoked to explain changes in climate, particularly abrupt ones, around the Atlantic Basin and globally on geological time scales (e.g., Rahmstorf 2002; Denton and Broecker 2008), motivating the study of its response to anthropogenic forcing and the interaction between natural variability and external forcing. An important objective of the U.S. AMOC program has been to quantify the importance of the AMOC in generating Atlantic SST variability and the role of the latter in global climate variability. Progress toward understanding the linkage between the AMOC and climate variability based on the five U.S. AMOC projects working in this area are described below.

In their project entitled "Assessing unstoppable change: ocean heat storage and Antarctic glacial ice melt", *Gilles and Matinson* seek to evaluate the Southern Hemisphere high-latitude heat storage from historical observations and models and assess poleward ocean heat transport. In 2012 they evaluated the overturning circulation to find a high correlation between surface and deep (top 2000 m) poleward heat transport south of 32°S. During the period of Argo observations, transport correlated with variations of the Southern Annular Mode (SAM) but not with ENSO. By comparing Argo-based estimates with in-situ observations, they confirmed that the float network provides a good estimate of the narrow East Antarctic Current transport.

In a project entitled "The contribution of Ocean Circulation to North Atlantic SST" *Kelly and Dickinson* aim to determine diagnostically and by using models, the role of the ocean in North Atlantic SST variability. Studying the time-scale dependence of ocean-atmosphere surface heat flux change in relation to SST variability, they find that while high-frequency variations are forced by the atmosphere (i.e., there is a positive correlation between downward heat flux and SST changes) the role is reversed in some regions when the observations are low-passed filtered, indicating the importance of low-frequency ocean heat advection.

In a diagnostic study of Atlantic decadal and multidecadal SST variability in observations and global climate models, *Kushnir with Ting* and other collaborators investigated mechanisms governing decadal SST variability in the North Atlantic and the impact those have on temperature and precipitation worldwide. In 2012 they continued their comparative study of models and observations of the pattern, timescale and impact of Atlantic multidecadal SST variability (AMV). Following their CMIP3-based study they find that the new generation of CMIP5 models also simulate well the patterns of AMV and its global impact but not the time variation. Their use of signal-to-noise maximizing EOF analysis shows again that a natural AMV mode is ubiquitous in all models whether in their control integration or when including anthropogenic forcing (GHG and aerosols). However, most models display much more rapid and less oscillatory variability than the impression derived from the short observational record.

Saravanan and Chang conducted a study of the impact of Atlantic low-frequency SST variability on climate extremes in the basin. Using a high resolution, coupled, regional model they found that with prescribed 20th century SSTs the model simulates the observed variations in the basin tropical cyclone energy. The model was also used to determine what processes govern the SST (and subsurface) bias in the tropical Atlantic that has persisted in early and present coupled GCMs. They find the cause lies in a local surface wind field bias that can be controlled by tuning model parameters. The model was also used for a study of subsurface ocean barrier layers and their influence of tropical storm intensification rates.

Straneo and collaborators (Straneo et al., 2012, 2013) conducted a study the glacier-ocean interactions in the large East-Greenland fjord with the objective of determining the oceanic processes that control the rate of submarine glacier melting, which can critically influence the stability of outlet glaciers. They find that present oceanic variability, including changing in the upper limb of AMOC, is rapidly transmitted to Greenland's glaciers with potential to affect glacier stability. This finding is supported by a paleo-reconstruction from a major glacial fjord.

There are presently only a handful of projects in the U.S. AMOC program studying AMOC-related climate impacts, and the program is seeking to increase its role in understanding AMOC impacts on sea ice, sea level changes, ocean ecosystems, and carbon sequestration. Several new DOE projects were added to the program in 2011 as a first step toward enhancing the program activities in these areas.

C. NEAR-TERM RESEARCH PRIORITIES

The near-term research priorities of the program reflect discussions at the 2012 annual U.S. AMOC science meeting (Boulder, CO, Aug. 15-17, 2012). Each Task Team reviewed the previous research prioirities that had been developed at the 2010 annual meeting in Miami, and which have since formed the primary focus of activity of the U.S. AMOC Task Teams. These near-term priorities are revisited here and updated to reflect the present consensus among the U.S. AMOC Science Team of the top science priorities that the program should attempt to address.

1. Observing system implementation and evaluation

Near-term priorities:

- Assessing the meridional coherence of AMOC changes is a continuing focus of prognostic models, state estimates and enhancement of the AMOC observing system. Although the RAPID array continues to provide observations in the subtropics, and Argo and altimetry have been used to estimate overturning variability at mid-latitudes in the North Atlantic, observing system enhancements are needed to provide estimates of overturning variability in the subpolar North Atlantic as well as in the South Atlantic.

As described previously, internationally-coordinated programs have been planned for the South Atlantic (SAMOC) and subpolar North Atlantic (OSNAP), which are currently waiting on final funding decisions.

- The importance of deep temperature and salinity measurements (i.e., deep Argo) in monitoring AMOC variability should also be assessed. At present, Argo, the primary component of the broad scale global ocean observing system for temperature and salinity, samples only the upper 2000 meters of the oceans. In many regions, this covers only the upper half or so of the southward flowing North Atlantic Deep Water. The importance of sampling temperature and salinity changes in the deep ocean remains unclear. More simulation efforts are needed to test the importance of deep water observations for constraining ocean models. Such work will provide guidance for building the deep ocean observing system by providing estimates for how many and what type of deep observations (e.g. deep Argo floats or full depth gliders) are needed.

- In addition to planning for enhancements of the AMOC observing system, critical efforts should be directed toward synthesizing observations from existing elements of the observing system. In particular, efforts should be made to compare the transport and transport variability of the flow field at Line W, RAPID-MOCHA and the MOVE array. In addition to this comparison of directly-measured flow fields, it is also desirable to place these array measurements in the broader context of satellite and Argo float observations across the North Atlantic. Finally, it is suggested that the US AMOC community consider the extent to which the proposed Oceanscope program could enhance the current and planned AMOC observing system and ocean state estimates.

2. AMOC state, variability, and change

Near-term priorities:

- As discussed in previous annual reports, it remains a high priority for the program to work toward the development of a multivariate fingerprint of the AMOC that would combine critical descriptors of the circulation and transport of ocean properties with those variables that are (or have been) observed extensively or can be reconstructed from paleoclimate archives. Studies aiming to develop fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations should be further encouraged and supported.

- Developing a set of metrics for the AMOC, in both depth and density spaces, has emerged as an important priority. In order to understand how AMOC variability relates to, is impacted by and/or impacts oceanic and atmospheric processes and properties, a set of metrics is desirable. For the convenience of multi-model comparison studies, various diagnostic variables currently not available in many climate models, such as AMOC in density coordinates needed for studying the meridional coherence of AMOC variability, are recommended to be provided by the climate modeling centers through the CMIP data archive.

- Assimilation modeling efforts should focus on reaching a consensus on the variability of the AMOC over the past few decades, and on placing realistic uncertainty bounds on these estimates. It is important that we understand the uncertainties of existing estimates and the accuracies required to detect climatically important AMOC-related changes.

- The meridional heat transport (MHT) carried by the AMOC provides the main connection to the climate system. Therefore it is important to explore AMOC and MHT relationships in various models (forward, assimilation, non-eddy-resolving, eddy-resolving) in comparison with observational data being generated by the program, to understand the reasons for differences, or biases, in the relationship between model AMOC intensity and MHT in available models.

Development of AMOC Fingerprints

To describe the past variability of the AMOC, as well as to evaluate AMOC impacts, it is desirable to define a "fingerprint", or characteristic signature, associated with AMOC fluctuations. The identification of such a fingerprint(s) will contribute to the interpretation of AMOC changes and will improve assessments of the impacts of AMOC variability on ecosystems, carbon cycles and global climate. A relatively simple index of the state of the AMOC is the zonally integrated meridional streamfunction, readily derived from ocean circulation models; however, historical observations are grossly inadequate to establish or verify such an index. In addition, to reconstruct the past variability of the AMOC when few direct observations were available, it will be necessary to develop proxies for the AMOC state estimate.

A recommended first approach to this is to assess the AMOC fingerprints that occur in an ensemble of climate models to determine whether or not a robust fingerprint can be established across a number of models. For example, Zhang (2008) identified a key fingerprint of AMOC variability through diagnostics analyses of observations and models. Her work suggests that the dipole pattern in the altimeter sea surface height and observed subsurface temperature between the North Atlantic subpolar gyre and Gulf Stream region can be used as a proxy for estimating AMOC variations. The models selected for the multi-model analyses need to be examined for biases in the climatological mean fields. Models with strong biases related to AMOC (such as Nordic Sea overflow, location of deep water formation sites) may provide misleading results and should be excluded from the analyses. AMOC fingerprints might be different for different time scales, so the time scale for the analyses should be clarified.

Analyses of paleoclimate records suggest there have been changes in the Atlantic climate system on several temporal scales. Some of the proxy records have the potential to resolve the relatively short times scales (decadal to millennial) needed to establish the range of Atlantic climate variability during the Holocene. Establishing the magnitude of Holocene Atlantic variability will aid efforts to understand whether an unprecedented (and perhaps abrupt) change in the AMOC due to anthropogenic forcing is underway. An evaluation of the currently available proxy data for relevance to AMOC can be used to motivate the collection of additional observations with which to assemble a longer or more detailed proxy record. Reconstructions from proxies that can be used to identify the fingerprint of AMOC variations through time are needed.

Task Team 2 organized an AMOC fingerprint mini-workshop at the 2012 U.S. AMOC annual meeting, and invited two paleoclimate experts (Casey Saenger and Ben Horton) to give presentations on SST and sea level proxies as potential candidates of AMOC proxies. Based on the outcome of these discussions, it is recommended that a separate international workshop on AMOC fingerprints be organized. In particular, Ben Horton reviewed the extensive, currently available proxies for sea level on the US East Coast, such as Salt Marshes which provide several thousand year records with decimeter vertical accuracy and decadal temporal accuracy. Could these sea level proxies be developed as AMOC proxies? The potential outcome in this research direction needs to be further explored.

Consensus and Uncertainties in Assimilation Efforts

Models that assimilate observations are powerful tools for estimating the state of the AMOC and diagnosing the drivers of AMOC change. Assimilation models provide a potential framework for creating estimates of the complete AMOC state (meridional volume and heat transports at all latitudes and all time scales, for example) by making simultaneous use of the complete historical observational data set within the framework of a model. Numerous estimates of overturning variability are available from ocean state estimates. However, a variety of approaches for assimilation is used by different groups, and agreement on AMOC volume and heat transports and their variability at different latitudes has not been clearly demonstrated across them. To understand the significant differences between estimates from various efforts, as well as differences with observations, it is necessary to place realistic uncertainty bounds on these estimates. A plan for developing such error estimates is needed in order to make the best use of the many ocean state estimates products that are available. The computational requirements to do this present a serious challenge, and few of the modeling groups producing AMOC state estimates have been able to allocate the computing resources needed to achieve this. Nevertheless, it remains an important objective, and efforts to produce such error estimates, and allocation of the necessary resources for it, should be encouraged. Efforts to further intercompare assimilation products and to assess their fidelity in reproducing known AMOC variability as characterized by observing systems such as the RAPID array should also be encouraged. Preliminary comparisons have been made between the RAPID data and some of the ECCO simulations, and also more recently with the MERCATOR and HYCOM-GODAE models. A more extensive comparison with other AMOC-related observations being performed by the program should also be carried out.

Relating AMOC Variability to Meridional Heat Transport

The ocean MHT in the North Atlantic at various latitudes is a fundamental climate variable regulating earth's climate in conjunction with its atmospheric counterpart. Various studies have estimated MHT at different latitudes based on available observations. Notably the RAPID array along 26.5°N provides the most robust estimate ever. It is important to explore AMOC and MHT relationships in various models (forward, assimilation, non-eddy-resolving, eddy-resolving) in comparison with the RAPID and other data sets to understand the reasons for differences or biases in the relationship between model AMOC intensity and MHT in available models, as compared to observations. Climate models often underestimate the climatological MHT at 26.5°N in comparison with the observations. Significant work has been done toward advancing this near-term priority in the past several years by Msadek et al. (2013), comparing the NCAR CCSM4 and GFDL CM2.1 models to RAPID observations. The results indicate that the bias is mainly due to errors in simulated temperature and velocity near the western boundary. Future improvements in climate model physics and resolutions are required for a better representation of the MHT and its relationship with the MOC at 26.5ºN.

The understanding of the AMOC and MHT relationships will also help with identifying the mechanisms for the AMOC variability and the linkage between the AMOC and the North Atlantic basin-averaged SST, i.e., AMV. It would also be useful to study the AMOC and MHT relationships at different time scales and different latitudes, because the contribution to the AMOC/MHT relationships from the surface wind forcing and the surface buoyancy forcing could be very different at various time scales and latitudes. In future studies, the modeling efforts of the AMOC/MHT relationships might be compared with the observations to be obtained from OSNAP and SAMOC programs. In addition, the ongoing satellite SSH observations and Argo measurements of ocean temperature, salinity and mid-depth circulation might also be used to estimate the AMOC/MHT relationships.

3. AMOC mechanisms and predictability

Near-term priorities:

- Further and focused effort needs to be directed toward understanding AMOC variability mechanisms, roles of atmospheric forcing and ocean – atmosphere feedbacks in this variability, and their model dependencies, utilizing all the available tools ranging from idealized theoretical models to the full general circulation models. A focused effort is also needed to develop a synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational data. These activities should be coordinated by the U.S. AMOC Science Team members.

- Contributions to ongoing near-term prediction and predictability efforts with a focus on the AMOC should continue. In addition to coordinated and focused analysis and inter-comparison of the CMIP5 decadal prediction simulations, notable AMOC-related climate events should be used for verification of these prediction experiments. These efforts should seek collaboration with the WCRP Decadal Climate Prediction Panel as well as the International CLIVAR Working Group on Ocean Model Development and the Global Synthesis and Observational Panel.

Assessment of various proposed mechanisms

It is still unclear which of the many proposed, mostly model-based mechanisms are more relevant to observed variability and how much each mechanism is dependent on specifics of each model. Recent studies suggest dominant roles for atmospheric forcing and ocean –

atmosphere interactions in AMOC variability, but the robustness of these findings has not been established. Another emerging question is related to stability (or regime) of the AMOC, i.e., are we in a stable AMOC regime at the present time? The biggest barrier towards answering these questions, particularly regarding mechanisms, is the lack of sufficient observational data to critically assess the realism of the model-based results. Therefore, we need to develop new observations and synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational information. This effort should be carried out in close collaboration with the program objective 1 to design and implement an AMOC monitoring system.

During the mini-workshop on AMOC mechanisms and predictability at the 2012 U.S. AMOC PI Meeting in Boulder, this near-term priority was discussed in detail. In order to make progress, the following action items were identified:

- Task Team 3 will develop coordinated and focused experiments with common perturbations applied to a hierarchy of models, ranging from idealized to complex, general circulation models, including eddy-resolving ocean components. The team will define experimental protocols, considering i) internal variability, e.g., advection and propagation of anomalies, ii) externally forced changes, e.g., aerosol forcing, momentum vs. buoyancy forcing, cold air outbreaks, and iii) model representations of subgrid scale physics, e.g., Nordic Sea overflows, meso- and submeso-scale parameterizations.

- Task Team 3 will support and join the efforts to have a fingerprint workshop with the paleo-climate community led by Task Team 2. The team will communicate with both the paleo-climate community through the CLIVAR / PAGES working group and the E.U. THOR project.

- To provide common analysis frameworks both for modeling studies and relevant observational analysis, Task Team 3 will identify and define a standard set of AMOC metrics. The team will coordinate with a related WGOMD CORE-II AMOC analysis project. These metrics will be made available through the U.S. CLIVAR AMOC web pages.

AMOC prediction and predictability

Progress continues on AMOC predictability and decadal prediction research led by climate modeling centers in the U.S. and around the world. U.S. AMOC recognizes that there are related ongoing efforts regarding analysis of these simulations. The U.S. AMOC program can provide coordination of AMOC related analysis and inter-comparison of model simulations. In addition, these decadal prediction experiments need to be verified against past climate change events, such as mid-1990s subpolar gyre warming in the North Atlantic and the sudden decrease in AMOC strength during 2009-2010. Such verification case studies should be coordinated, using a standard set of metrics. The mini-workshop discussions at the 2012 PI meeting, have identified the following action item:

- Task Team 3 will continue to contribute to ongoing prediction and predictability activities. In particular, the team will participate in or organize a case verification study, focusing on the representation of the sudden AMOC decrease in 2009-2010 in the existing prediction simulations. A standard set of metrics will be employed.

Proper initialization of decadal prediction simulations and bias correction of the solutions are still the two biggest issues, with no clear best-practice choices. The former involves data assimilation products and ocean hindcast simulations. It is very important that studies on these topics as well as the related collaborations between the U.S. modeling centers continue to make decadal climate prediction a useful reality.

4. Climate sensitivity to AMOC: climate/ecosystem impacts

Near-term priority:

- Further study is required to understand the connections between AMOC/North Atlantic SST and climate variability elsewhere, the physical mechanisms of these teleconnections, and the related impacts on humans and ecosystems. Targeted studies of the impact of AMOC variability on sea ice, ocean ecosystems, sea level changes around the Atlantic Basin, and the exchange of carbon between the atmosphere and ocean are also needed.

In the last year progress report, we identified the need of expanding the scope of AMOC's impact studies to include its effect on ecosystems, sea-ice, sea-level changes and atmosphere-ocean carbon exchange and recommended a dedicated session on these topics at 2012 U.S. AMOC PI meeting as an effective way of entraining experts in these areas of research into the AMOC community. As a result, one of the mini-workshops during the last U.S. AMOC PI meeting was on the AMOC's impact on carbon cycles. The following is a summary of the mini-workshop discussions pertinent to near-term priorities of Task Team 4.

Understanding AMOC's Impact on Carbon Cycle

The mini-workshop was guided by three fundamental scientific questions: *1) What is the role of AMOC in global biogeochemical cycles, in particular carbon cycles? 2) Does AMOC variability affect variability of carbon cycles? 3) What are future projections regarding the role of AMOC in the global carbon cycle response to greenhouse warming?*

Regarding question (1), there is compelling evidence that the AMOC is important for the mean distribution of carbon in the ocean, particularly in the subpolar North Atlantic where the AMOC plays an important role in Atlantic Ocean CO_2 uptake. However, it is noted that large discrepancies exist between model simulations of mean distribution of carbon and observations. Models also fail to simulate realistic seasonal carbon cycle in the North Atlantic Ocean. The failure of the models appears to be mainly caused by poor representations of physical processes related to the AMOC, although erroneous representation of biological processes may also be a contributing factor. The importance of the AMOC in oceanic CO_2 uptake and the challenge of climate models in simulating carbon cycle make the North Atlantic Ocean an ideal region for a focused study of carbon processes, which requires that physical and biogeochemical communities work together on the problem.

Concerning question 2) and 3), there is observational evidence of large decadal variability in oceanic pCO_2 in the North Atlantic. In fact, the observed decadal variability is stronger than the long-term pCO_2 trend. However, it is not clear at present what drives the strong decadal pCO_2 variability due to lack of observations. In particular, current observations are not sufficient to link carbon variability to AMOC/AMV variability in the North Atlantic. On the other hand, a very recent study by Pérez et al. (2013) shows that there was a rapid decline of oceanic uptake of atmospheric CO_2 in the subpolar North Atlantic during 1990-2006, which may be attributable to a slowdown of the AMOC. Clearly, there is a need for an enhanced observational network and for improved model carbon simulations in the North Atlantic in order to fully delineate the relationship between carbon variability and AMOC variability. Understanding this relationship is critically important for addressing question 3) - *What are future projections regarding the role of AMOC in the global carbon cycle response to greenhouse warming?*

Recognizing the importance of these issues, it is proposed that the understanding of the role of the AMOC in the carbon cycle be set forth as a near-term research priority of the program. The following is a list of specific recommendations for action:

- Organize a workshop that brings physical and biogeochemical communities together, focusing on the understanding of basic carbon processes, such as seasonal cycle, in the North Atlantic.

- Enhance the carbon observation network in the North Atlantic, including biogeochemical Argo floats and *in situ* biogeochemical observations.

- Improve model simulations by 1) organizing a coordinated CORE-type ocean model intercomparison study focusing on carbon cycle simulation in the North Atlantic, 2) working together with the CMIP5 community on diagnosing and understanding North Atlantic carbon cycle processes within the CMIP5 model ensemble, and 3) collaborating with the ocean data assimilation community and working towards ocean carbon data assimilation.

Understanding the link between AMOC and SST variability

The issue concerning the linkage between the AMOC and SST and upper ocean thermal variability remains one of the most important and pressing challenges of the Task Team 4. Of particular importance are the questions of how AMOC variability in the subpolar North Atlantic expresses itself in terms of basin-wide SST change and how this SST change affects the atmosphere and climate variability. Understanding these questions has important implications for understanding potential impacts of the AMOC on the tropical Atlantic ITCZ, the West Africa Monsoon, and extreme climate events (such as hurricanes) within the Atlantic sector.

New results emerging from some recent studies suggest that the North Atlantic storm track may be an active participant in determining how the AMOC responds to greenhouse warming. For example, Woollings et al. (2012) indicate that an increase in meridional SST gradient in the North Atlantic due to the combined effect of greenhouse-induced warming and AMOC-induced SST change in the subpolar North Atlantic can lead to an increase in the atmosphere baroclinity and thus an increase in North Atlantic storm track activity. Wan et al. (2013) show that an intensified North Atlantic storm track can lead to an increase in the AMOC through enhanced deep convection in the subpolar North Atlantic. Together these recent studies point to a potential role of ocean-atmosphere interactions, via North Atlantic storm track, in long-term AMOC change. There is a clear need to further understand this problem through a concerted observational, theoretical and modeling effort.

Another important topic that has emerged from recent studies concerns the role of aerosol forcing in driving multi-decadal North Atlantic climate variability. Booth et al. (2012) argue that a significant portion of North Atlantic decadal SST variability can be attributed to aerosol forcing, suggesting aerosol forcing as a prime driver of 20th century North Atlantic decadal climate variability. This analysis, based on a simulation with the recent version of the Hadley Center coupled Earth System model, was criticized by Zhang et al. (2013) based on the difference between the SST response to the aerosol forcing and that related to AMOC variability. This raises an important question concerning the simulation of aerosol forcing in coupled models, particularly aerosol indirect effects, and the impact on the AMOC and North Atlantic decadal SST variability. Future studies are clearly needed to quantify this vital issue, as the outcome obviously has important bearing on the understanding of AMOC's impact on climate.

Other Impacts of AMOC

The AMOC's potential impact also extends to ocean ecosystems (e.g., Nye et al. 2011), sea-ice, sea-level changes around the Atlantic Basin (Yin et al. 2010; Yin 2012) and sea ice in the marginal northern seas and the Arctic Ocean. At present, studies in these areas are not well represented in the U.S. AMOC science team. To assure a well-balanced research program that addresses all of the important challenges related to AMOC variability, a concerted effort is needed to entrain experts in these research areas to the U.S. AMOC science team and provide them opportunities to interact with U.S. AMOC PIs. This should be considered as a near-term priority of Task Team 4.

Robustness of AMOC/AMV impacts and connecting impact studies to societal needs

While the number of studies on AMOC/AMV impact on world (particularly Northern Hemisphere) climate has increased and broadened, more should be done to quantify these links in terms of their impact on society in a format that could assist decision makers in various sectors (e.g., in water resources, coastal infrastructure, health, and ocean resource management). This will help focus impact research and lead to tangible benefits from AMOC research.

Strengthen links to other related CLIVAR/WCRP activities

The program should aim to raise the profile of U.S. AMOC research to help foster exchange of information and to stimulate collaborative progress. This goal can be achieved through U.S. CLIVAR, the International CLIVAR Atlantic Implementation Panel, and through communication with individual program committees, nationally and internationally, such as CLIVAR Working Group on Ocean Model Development (WGOMD), WCRP Working Group on Coupled Modeling and others.

D. RELATED ACTIVITIES TO SUSTAIN

1. Required large-scale observations

Many of the research projects that are part of the U.S. AMOC program will involve the analysis and synthesis of data from elements of the large-scale sustained observing system, including current and proposed satellite and *in-situ* observational platforms (e.g., Argo). The requirements for sustained large-scale observations have been described in detail in the 2010 U.S. AMOC Science Team report. They have remained (and will for the foreseeable future remain) the same. If anything, evidence is mounting for the urgent need to maintain global-scale continuous observing systems to understand climate variability on decadal time scales and beyond. Detailed requirements for a sustained ocean observing system were established at the OceanObs'09 Conference (http://oceanobs09.net) in Venice, September 2009. The primary responsibility for the design and implementation of these observing systems lies with NASA, NOAA, NSF and international partners and requires resources above those that can be explicitly provided by the U.S. AMOC Program.

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 is of central importance to the U.S. AMOC goals. Communication and collaboration with the paleoclimate community on the identification and use of proxy records to fingerprint AMOC variability is being pursued. In order to identify fingerprints of AMOC variability on decadal and centennial (dec-cen) scales:

a) The spatial coverage of paleoclimate data needs to be expanded. There are probably fewer than a dozen deep ocean records in the North Atlantic that are suitable to resolve dec-cen change. This is in contrast with hundreds to thousands of sites on land around the North Atlantic basin.

b) The temporal resolution of paleoclimate data needs to be improved. To resolve dec-cen changes requires sampling at the centimeter scale (very expensive) and dating very closely.

c) Sufficient well-resolved sites are needed to determine if the observed paleo changes are truly cyclical.

d) 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.

e) The relationship between additional variables and the AMOC needs to be explored. The recent work by Straneo et al. (2011, 2012) suggests that marine glaciers may be responding to large-scale oceanic conditions. Analyses of AMOC state and variability should be sensitive of the need for viable paleoclimate proxies, and explore the relationship between potential proxies and AMOC state using all of the available tools. High-resolution temperature records from a southern Caribbean sediment core show anti-correlated surface and subsurface temperature changes during the last deglacial transition (Schmidt et al. 2012) and may be used as an AMOC proxy.

f) High resolution sea level proxies during the Holocene, such as those published by Kemp et al. (2011), provide a unique opportunity to link the instrumental record with the paleoclimate record if sufficient understanding of the sea level signals related to the AMOC can be developed. Further development of such records as well as their interpretation should continue to be supported.

3. Modeling capabilities

The development of a predictive understanding of the AMOC depends heavily on the use of numerical models as evidenced from the summary of the progress given in section B.3 and the individual project reports in Appendix 4. 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 are 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, is a key aspect 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 (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-art climate models, are crucial. Some of the new results summarized in the Section B.3 indicate a need for eddy-resolving resolution in the ocean models to properly simulate many processes crucial to AMOC. These activities require:

a) Sustained support for both the high-end coupled modeling activities at the large U.S. national laboratories, including NCAR and GFDL, and high-end computers (as exemplified by the opening of the new NCAR Wyoming Supercomputing Center). The required length of high resolution (i.e. eddy-resolving) ocean – sea-ice coupled and fully-coupled simulations for use in AMOC variability studies, despite the new resources, still remains inhibited by the computing resources available to climate researchers today. This may be a key rate-limiting step toward improved modeling capabilities and longer integrations (at high resolution) needed for decadal and centennial studies of AMOC variability. Sustaining and substantially augmenting computing resources for simulations and prediction of the AMOC remains a high priority.

b) Continued support for process-based and idealized modeling studies within the academic research community, particularly at universities. This requires sustained access to computing resources, such as through the NSF Climate Simulation Laboratory (http://www.cisl.ucar.edu/csl/) that supports computer intensive climate modeling work.

c) Support for the development and improvement of model parameterizations. Studies indicate that the AMOC and its variability are strongly influenced by processes that remain below the grid scale of most models used in climate simulations and are therefore parameterized. Continued support to improve model parameterizations and to incorporate new ones to represent missing physics should parallel the efforts to increase model resolution and to understand processes better. This support is important because relatively coarse resolution models will remain as the workhorse models to study AMOC variability for the next few years as they are affordable to perform long simulations.

d) Sustained infrastructure that makes climate model output easily available over the Web. Model outputs from the IPCC Fifth Assessment Report (AR5) include prediction experiments with strong AMOC relevance. It is vital that scientists studying AMOC variability and predictability have open access to such model data sets from state-of-the-art coupled models.

e) Support for the infrastructure to analyze large climate model outputs. As the climate models and earth system models have increasing number of components and increasingly high resolution, the analysis of these model data is becoming challenging. Therefore, investment in the methods and infrastructure for the efficient analyses of the large model outputs are crucial. Especially, ensuring access to those infrastructures from the academic research community outside of the major modeling centers is very important.

f) 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 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. Studies that demonstrate the relative impacts of existing observations in constraining the estimated AMOC state should continue to be encouraged and augmented.

g) Sustained support for assimilation efforts beyond ocean data assimilation. The coupled nature of the ocean-atmosphere system demands a coupled approach towards state estimation. There are already ongoing efforts for coupled ocean-atmosphere data assimilation used to study the AMOC. Such efforts complement the projects funded under U.S. AMOC for ocean model-based synthesis and observing system design studies. These efforts should be sustained and augmented in the future.

E. FUNDING

1. FY 2012 agency support

NASA, NOAA, NSF, and DoE, the federal agency sponsors of the U.S. AMOC Science Program in FY 2012, funded a total of 52 projects supporting the work of approximately 100 U.S. scientists (see Appendix 2). NASA provided $760K to support 8 projects exploiting NASA satellite observations and model-assimilated data sets, and characterizing the attributes, variability and mechanisms of the AMOC. NOAA allocated over $5.3M to a total of 12 projects, including sustained observations AMOC analysis, modeling and predictability studies. Twenty NSF-funded projects received $7.9M in incremental funding to document AMOC state and variability, improve understanding of AMOC mechanisms and predictability, and examine the links between AMOC and climate variability. DoE provided $1.92M in support of 12 modeling studies examining the mechanisms of AMOC variability and predictability as well as the influence of AMOC on climate variability and changes.

The four agencies, through their support of the U.S. CLIVAR Project Office budget, financed a Summer 2012 U.S. AMOC Science Meeting held at the National Center for Atmospheric Research in Boulder, Colorado, August 15-17, 2012. The meeting assembled U.S. AMOC principal investigators, invited speakers, and other interested U.S. and international scientists, to share progress toward near term research priorities and establish future research directions, which are reflected in this annual report.

2. FY 2013 and beyond

With the completion of 8 projects during 2012, there are 44 ongoing U.S. AMOC projects supported by NASA, NOAA, NSF and DOE at the start of FY 2013. NASA has solicited new projects in its ROSES-2012 Research Announcement for analysis and interpretation of the ocean circulation using satellite and *in-situ* data. NOAA has solicited new projects in its 2013 Climate Program Office Announcement, inviting focused multi-model analyses and experimentation to better understand the mechanisms of AMOC variability and predictability in different models. NSF will accept new AMOC project proposals through its standard solicitations for Physical Oceanography and Atmospheric and Geospace Sciences. DOE has committed FY 2013 funding to the second joint solicitation with NSF and the Department of Agriculture for Decadal and Regional Prediction using Earth System Models (EaSM).

Through their support of the U.S. CLIVAR Project Office 2013 budget, the funding agencies are contributing to U.S. AMOC-U.K. RAPID International Science Meeting on AMOC Variability: Dynamics and Impacts to be held in Baltimore, Maryland, July 16-19, 2013. The meeting is designed to explore the full breadth of AMOC research from paleo and modern observational studies, theory, modeling, predictability, prediction, and impacts on climate, carbon and biogeochemistry. The format will address three themes:

- Observations and dynamics of seasonal-to-inter-annual timescales (results from recent instrument deployments and related observational studies, and results from regional high-resolution modeling);
- Observations and dynamics of decadal to multi-centennial timescales (results from proxy studies, and coupled climate model simulations); and
- Climate impacts (studies focused on forecasts of societal impacts, including changes in key variables: SST, sea level, carbon/biogeochemistry, and ecosystems).

The President's budget for all four agencies provides steady-state resources (including a restoration of the FY 2012 reduction in NOAA) such that current commitments would be fulfilled through FY 2013. Agencies report that they would seek to continue to invite and support new and renewal projects through their regular solicitation processes, subject to the availability of funds through appropriations and agency allocation decisions.

F. SUMMARY

The U.S. AMOC Program, now in its fifth year, was developed as a U.S. interagency program to increase understanding of the Atlantic Meridional Overturning Circulation, in response to the 4th near-term priority of the SOST Ocean Research Priorities Plan. The purpose of the program is to bring together researchers studying the AMOC, and to build partnerships among modeling and observational groups to address problems related to AMOC variability, predictability, and climate impacts. During 2012 the program was constituted by over 50 funded projects. Annual program meetings, held either independently or jointly with the U.K. RAPID annual meetings, have been very successful in bringing together the program PIs to share research results, develop collaborative projects, and identify near-term research priorities.

Research highlights and accomplishments of the program are reviewed within the body of this document, as are updates to the main research priorities resulting from discussions at the 2012 annual PI meeting held in Boulder, CO. The research highlights described herein show that our knowledge of AMOC variability and its linkages to climate variability is advancing, but that a full understanding of AMOC variability throughout the basin, and the mechanisms controlling its variability, has yet to be achieved. Based on the progress made during 2012, the present status of the program and the important near term goals going forward can be summarized as follows:

1. Strong efforts were put forth during 2012 toward the design of AMOC observing systems in the subpolar North Atlantic (OSNAP) and subtropical South Atlantic (SAMOC), in collaboration with international partners. Proposals were developed and submitted to funding agencies supporting the U.S. AMOC program. SAMOC has not received full support, although some elements are in place. The US OSNAP proposal anticipates a funding decision in May of 2013.

2. Observing system simulation experiments (OSSEs) using high-resolution ocean models are increasingly being used to test observing system strategies for the AMOC, notably in the above SAMOC and OSNAP program efforts, and also to assess needs for deep observations to constrain the AMOC state and variability (e.g., deep Argo). Studies based on ocean state estimates and adjoint models to understand the AMOC sensitivity to regional perturbations and key measurements that may be required in such regions to monitor and predict the AMOC state and to understand the nature of its variability are also in progress.

3. Results from several of the *in-situ* programs established as part of the AMOC monitoring network (RAPID, Line W, MOVE) are now approaching—or exceeding—a decade in length, and are becoming increasingly valuable. For example, the RAPID array has shown a significant decrease in the AMOC strength at 26.5°N during the past few years in association with a downturn in the NAO index. The ability to monitor the AMOC state and ocean heat transport using satellite and Argo data at certain latitudes where boundary transport measurements are not vital has also been demonstrated, and these methods can potentially be extended to other latitudes where boundary array measurements are available. At the same time, ocean state estimates and reanalyses are increasingly being developed and applied to study the AMOC. A high priority for the program in coming years will be to synthesize all of the results from the *in-situ* array programs and combine them with the state estimate models to develop a firm understanding of AMOC changes that are currently taking place or that have taken place in the recent past.

4. Recent studies have demonstrated that the measure of the AMOC is spatially, as well as temporally, variable. As such, there is no longer an expectation that an overturning index based on the zonally-integrated meridional flux of mass at one latitude will be coherent with that at another latitude. A near-term priority of the program is to develop a common set of metrics for the AMOC, in both depth and density spaces, that can be derived and compared between models and observations. For the convenience of multi-model comparison studies, various diagnostic variables currently not available in many climate models, such as AMOC in density coordinates needed for studying the meridional coherence of AMOC variability, are recommended to be provided by the climate modeling centers through the CMIP data archive.

5. Model studies have suggested that there is an identifiable 'fingerprint' associated with AMOC variability, manifested in measurable broad-scale fields such as sea level and subsurface temperature patterns. Work toward developing such fingerprinting techniques to extend the AMOC record back in time using both the historical instrumental record and high-resolution paleo proxy data is continuing. A near-term priority of the program is to develop robust multivariate fingerprints of AMOC variability based on multi-model analysis, and to explore the possibility of using long-term coastal sea level records as a proxy for AMOC variability.

6. Progress has been made in improving our understanding of AMOC variability mechanisms and of the roles of atmospheric forcing and ocean – atmosphere interactions in this variability, based on diverse approaches, including process-oriented modeling, sensitivity studies using adjoint modeling, application of transfer function approach, eddy-resolving general circulation modeling, interactive-ensemble coupled experiments, forced ocean – sea-ice hindcast simulations, and intercomparison studies of CMIP5 models and simulations. Despite progress, findings continue to be model dependent. To address this major issue, a community effort has been initiated to perform coordinated and focused experiments across

a hierarchy of approaches to further our understanding of AMOC mechanisms, using a common set of metrics.

7. AMOC prediction and predictability continue to be a main focus of the major climate modeling centers. Results from ensemble decadal prediction experiments continue to show measurable skill in predicting AMOC and heat content anomalies in the North Atlantic, with some suggesting potential predictability up to a decade in advance and others showing more limited predictive skill. Further effort needs to be directed toward assessing the robustness and model dependency of the predictions, and to determine the best practices for model initialization and model bias correction. These efforts can be advanced through focused inter-comparisons of the existing IPCC AR5 decadal prediction experiments, complemented by additional, coordinated verification studies where the U.S. AMOC program can play a coordinating role.

8. Much more research has been accomplished linking global climate and precipitation variability to changes in the AMO/AMV SST patterns in the Atlantic. The widespread impacts of AMV are being clearly elucidated by U.S. AMOC investigators and other researchers, but further study is needed to understand the physical linkages between AMOC variability and SST variability over the Atlantic, especially the connection between the AMOC and AMV. In addition, the U.S. AMOC program is trying to expand its scope of AMOC impact studies to problems involving sea level, sea ice, ocean ecosystems, and carbon uptake, by recruiting new PIs who are active in these areas and by building bridges to other programs with mutual research interests.

9. Elements of the AMOC have been recognized by the U.S. CLIVAR Working Group on Greenland Ice Sheet-Ocean Interactions (GRISO) to play a potentially important role in contributing to the recent speedup of Greenland's marine-terminating outlet glaciers, notably through changes in the circulation in the subpolar gyre and associated increased penetration of Atlantic waters into Greenland's fjords. The GRISO WG has identified this issue as an important topic for further focused research that should interface with the U.S. AMOC Program.

Finally, a strong recommendation coming from discussions at the 2012 annual PI meeting is that the U.S. AMOC Program and supporting agencies should seek to fully exploit the synergy of the AMOC Science Team. The 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 be strongly encouraged.

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APPENDIX 1. Terms of reference for the U.S. 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*
Gustavo Goni	*NOAA Atlantic Oceanographic and Meteorological Laboratory*
Patrick Heimbach (Vice-chair)	*Massachusetts Institute of Technology*
Bill Johns	*University of Miami*
Felix Landerer	*Caltech/NASA Jet Propulsion Laboratory*
Craig Lee	*University of Washington*
Susan Lozier (Chair)	*Duke University*
Chris Meinen	*NOAA Atlantic Oceanographic and Meteorological Laboratory*
Thomas Rossby	*University of Rhode Island*
Uwe Send	*Scripps Institution of Oceanography*
John Toole	*Woods Hole Institution of Oceanography*

The team is charged with the design and implementation of an AMOC monitoring system. AMOC monitoring in the U.S. 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:

- Development of a sustained and integrated observing system for AMOC variability in coordination with international partners;
- The design of AMOC monitoring systems for the subpolar North Atlantic and subtropical South Atlantic; and
- Assessing the importance of deep temperature and salinity measurements in monitoring AMOC variability.

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*
Sirpa Häkkinen	*NASA Goddard Space Flight Center*
Kathie Kelly	*University of Washington*
Tony Lee	*California Institute of Technology/Jet Propulsion Laboratory*
Jonathon Lilly	*University of Rhode Island*
Susan Lozier	*Duke University*
Julian McCreary	*University of Hawaii*
Mike McPhaden	*NOAA Pacific Marine Environmental Laboratory*
Peter Rhines	*University of Washington*
Irina Rypina	*Woods Hole Oceanographic Institution*
C.K. Shum	*Ohio State University*
Fiamma Straneo	*Woods Hole Oceanographic Institution*
Josh Willis (Chair)	*NASA Jet Propulsion Laboratory*
Xiao-Hai Yan	*University of Delaware*
Rong Zhang (Vice-chair)	*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:

- Assessing the meridional coherence of AMOC changes throughout the basin on different time scales through observations and prognostic and state estimation models;
- Assimilation modeling efforts focused on the variability of AMOC over the past few decades, placing realistic uncertainty bounds on these estimates and understanding the uncertainties in existing estimates;
- Developing fingerprinting techniques to better characterize AMOC variability by combining models and observations; and
- Exploring the AMOC and meridional heat transport relationships in various models.

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*
Alan Condron	*University of Massachusetts*
Ruth Curry	*Woods Hole Oceanographic Institution*
Gokhan Danabasoglu (Chair)	*National Center for Atmospheric Research*
Tom Delworth	*NOAA Geophysical Fluid Dynamics Laboratory*
Shenfu Dong	*University of Miami*
Alexey Federov	*Yale University*
Chris Hill	*Massachusetts Institute of Technology*
Aixue Hu	*National Center for Atmospheric Research*
Jong Kim	*Argonne National Laboratory*
Young-Oh Kwon (Vice-chair)	*Woods Hole Oceanographic Institution*
Julian McCreary	*University of Hawaii*
Robert Pickart	*Woods Hole Oceanographic Institution*
Tony Rosati	*NOAA Geophysical Fluid Dynamics Laboratory*
Eli Tziperman	*Harvard University*
Wilbert Weijer	*Los Alamos National Laboratory*
Jiayan Yang	*Woods Hole Oceanographic Institution*
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:

- Understand AMOC variability mechanisms and the model dependencies of these variability mechanisms through detailed comparison study coordinated among the large modeling groups;
- Develop a synthesis of existing observations to discriminate various model-based proposed mechanisms against the observational data; and
- Coordinate with IPCC AR5 centers on an intercomparison study of the robustness of AMOC predictions among simulations using various models.

The task team will also coordinate with the U.S. 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*
Ping Chang (Chair)	*Texas A&M University*
Sarah Gille	*Scripps Institution of Oceanography*
Kathie Kelly	*University of Washington*
Yochanan Kushnir (Vice-chair)	*Columbia University/Lamont-Doherty Earth Observatory*
Zhengyu Liu	*University of Wisconsin*
R. Saravanan	*Texas A&M University*
Fiamma Straneo	*Woods Hole Oceanographic Institution*
Anastasios Tsonis	*University of Wisconsin*

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:

- An assessment of the links between AMOC variability and changes in Atlantic tropical storm activity, fluctuations in the sub-Saharan Sahel region rainfall, U.S. hydroclimate, and remote connections such as decadal variability of the Asian monsoon intensity; and
- Targeted studies on the impact of AMOC variability on sea ice, ocean ecosystems, sea level changes, and the exchanges of carbon between the atmosphere and ocean.

APPENDIX 2. AMOC projects currently underway or recently funded

Principal Investigator	Co-PIs	Project Title	Sponsor	Duration
Molly Baringer (NOAA/AOML)	C. Meinen and S. Garzoli (NOAA/AOML)	Western Boundary Current Time Series (WBTS)	NOAA	2000 – Ongoing
Molly Baringer (NOAA/AOML)	S. Garzoli and G. Goni (NOAA/AOML)	State of the Climate: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean	NOAA	2006 – Ongoing
Lisa Beal (U Miami)	Z. Garraffo (U Miami)	Pathways and Variability of NADW from the Atlantic Ocean, in two eddy-resolving models	NSF	05/2010-04/2013
Amy Bower (WHOI)	M. Spall (WHOI)	A Crossroads of the AMOC: The Charlie-Gibbs Fracture Zone	NSF	10/2009-09/2014
Grant Branstator (NCAR)	H.Teng and G. Meehl (NCAR), A. Gritsun (RAS)	Initial Value Predictability of Intrinsic Oceanic Modes and Implications for Decadal Prediction over North America	DOE	09/2010-08/2013
James Carton (U Maryland)	B. Giese (Texas A&M)	SODA: Exploring Centennial Changes in Ocean Circulation	NSF	06/2008-05/2013
James Carton (U Maryland)	S. Grodsky (U Maryland), R. Lumpkin (NOAA/AOML)	Using Historical Surface Data to Verify the Twentieth Century Reanalysis for Oceanographic Applications	NOAA	09/2011-08/2012
James Carton (U Maryland)	M. Steele (U Washington)	Using ocean data assimilation to explore Arctic/subarctic climate variability	NSF	09/2012-08/2015
Paola Cessi (UCSD/SIO)		Pulling the Meridional Overturning Circulation from the South	DOE	09/2010-08/2013
Ping Chang (Texas A&M)	L. Ji (Texas A&M), B. Kirtman (U Miami)	Role of Atmospheric Variability in the AMOC	NOAA	09/2011-08/2012
Ping Chang (Texas A&M)	R. Saravanan (Texas A&M), J. Hsieh (Texas A&M)	Study of the Frontal-Scale Air-Sea Interaction along the Gulf Stream Extension Using a High-Resolution Coupled Regional Climate Model	NSF	08/2011-07/2014
Wei Cheng (U Washington)	D. Zhang (U Washington)	Assessing the AMOC in Climate Models	NOAA	03/2011-03/2012
Alan Condron (U Massachusetts)	R. Bradley (U Massachusetts)	High-Resolution Model Development to Quantify the Impact of Icebergs on the Stability of the AMOC	DOE	09/2011-09/2014
Ruth Curry (WHOI)	J. Deshayes (WHOI)	Fresh Water Content and Circulation Variability in the North Atlantic: Are they Related?	NSF	03/2008-02/2012

Principal Investigator	Co-PIs	Project Title	Sponsor	Duration
Ruth Curry (WHOI)	K. Polzin (WHOI)	Dynamics of Abyssal Mixing and Interior Transport Experiment (DynAMITE)	NSF	11/2009-10/2013
Gokhan Danabasoglu (NCAR)	T. Delworth and A. Rosati (NOAA/GFDL), J. Marshall (MIT), J. Tribbia (NCAR)	A Collaborative Investigation of the Mechanisms, Predictability, and Climate Impacts of Decadal-Scale AMOC Variability Simulated in a Hierarchy of Models	NOAA	09/2009-08/2012
Tom Delworth (NOAA/GFDL)	A. Rosati and R. Zhang (NOAA/GFDL)	Decadal Climate Predictability and Abrupt Change	NOAA	2010-Ongoing
Shenfu Dong (U Miami)	G. Goni, M. Baringer and G. Halliwell (NOAA/AOML)	Assessing the Sensitivity of Northward Heat Transport/AMOC to Forcing in Existing Numerical Model Simulations	NOAA	05/2010-04/2013
Kathleen Donohue (U Rhode Island)	C. Flagg (SUNY/SB), T. Rossby (U Rhode Island)	The Oleander Project: Sustained Observations of Ocean Currents in the NW Atlantic between New York and Bermuda	NSF	09/2008-08/2013
Alexey Fedorov (Yale U)		A Generalized Stability Analysis of the AMOC in Earth System Models: Implication for Decadal Variability and Abrupt Climate Change	DOE	09/2011-09/2014
Sarah Gille (UCSD/SIO)	D. Martinson (Columbia U/LDEO)	Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt	NOAA	05/2010-04/2013
Gustavo Goni (NOAA/AOML)	M. Baringer and S. Garzoli (NOAA/AOML)	The Ship of Opportunity Program	NOAA	Ongoing
Patrick Heimbach (MIT)	R. Ponte (AER), C. Wunsch (MIT)	Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period	NOAA	05/2010-04/2013
Patrick Heimbach (MIT)	R. Ponte (AER), C. Wunsch (MIT)	Collaborative Research: An eddy-permitting Arctic & Sub-Polar State Estimate for climate research	NSF	09/2010-08/2013
Chris Hill (MIT)	P. Winsor (U Alaska)	Abrupt Climate Change and the AMOC – Sensitivity and Non-Linear Response to Arctic/Sub-Arctic	DOE	07/2008-07/2012
Aixue Hu (NCAR)	W. Washington and G. Meehl (NCAR)	Role of the AMOC on Past and Future Climate Changes	DOE	01/2006-12/2012
Bill Johns (U Miami)	L. Beal (U. Miami), C. Meinen and M. Baringer (NOAA/AOML)	An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic	NSF & NOAA	01/2008-01/2014
Kathryn Kelly (U Washington)	L. Thompson (U Washington)	Assessing Meridional Transports in the North Atlantic Ocean	NASA	10/2008-09/2012

Principal Investigator	**Co-PIs**	**Project Title**	**Sponsor**	**Duration**
Kathryn Kelly (U Washington)	S. Dickinson (U Washington)	The Contributions of Ocean Circulation to North Atlantic SST	NASA	02/2010-01/2013
Jong Kim (Argonne National Lab)	W. Collins (LBNL)	Investigation of the Magnitudes and Probabilities of Abrupt Climate Transitions	DOE	06/2008-05/2013
Yochanan Kushnir (Columbia U/LDEO)	R. Seager and M. Ting (Columbia U/LDEO), E. Tziperman (Harvard U)	Atlantic Multideca dal Variability: Mechanisms, Impact, and Predictability: A Study Using Observations and IPCC AR4 Simulations	NOAA	08/2009-07/2012
Young-Oh Kwon (WHOI)	C. Frankingoul (WHOI), G. Danabasoglu (NCAR)	Decadal Variability of the AMOC and its Impact on the Climate: Two Regimes and Rapid Transition	NOAA	05/2010-04/2013
Craig Lee (U Washington)	R. Moritz, J. Gobat and K. Stafford (U. Washington)	The Arctic Observing Network at Critical Gateways—A Sustained Observing System at Davis Strait	NSF	09/2010–08/2015
Jonathan Lilly (NW Research Associates)	K. Dohan (ESR), T. Rossby (U Rhode Island), F. Straneo and M. Spall (WHOI)	Mode Water Formation in the Lofoten Basin: A Key Element in the Meridional Overturning Circulation	NSF	06/2009–05/2013
Zhengyu Liu (U Wisconsin)	Bette Otto-Bliesner (NCAR)	Simulating and Understanding Abrupt Climate-Ecosystem Changes during Holocene with NCAR-CCSM3	DOE	08/2008-07/2012
Julian McCreary (U Hawaii)	R. Furue, A. Timmerman and F. Schloesser (U Hawaii)	Dynamics of the Descending Branch of the AMOC	NSF	06/2009–05/2013
Michael McPhaden (NOAA/PMEL)	D. Zhang and W. Cheng, (U Washington)	Decadal and Multidecadal Variability of the AMOC in Observational Records and Numerical Models	NOAA	05/2010-04/2013
Chris Meinen (NOAA/AOML)	S. Garzoli, M. Baringer and G. Goni (NOAA/AOML)	South Atlantic Meridional Overturning Circulation (SAMOC)	NOAA	10/2008-9/2012
Robert Pickart (WHOI)	M. Spall (WHOI)	Denmark Straight Overflow Water: A New Paradigm for the Origin of the Deep Western Boundary Current	NSF	12/2010-11/2014
Peter Rhines (U Washington)	S. Häkkinen (NASA/GSFC)	Pathways of Meridional Circulation in the North Atlantic Ocean	NASA	10/2008 – 09/2012
Peter Rhines (U Washington)		Deep Ocean Mixing and Circulation in the Subpolar Seas	NSF	08/2009-07/2012
Peter Rhines (U Washington)	C. Eriksen (U Washington)	Analysis of Eddies, Mixing, and Dense Overflows at the Iceland-Faroe Ridge in the Northern Atlantic Ocean Observed with Seagliders	NSF	09/2010-08/2013

Principal Investigator	Co-PIs	Project Title	Sponsor	Duration
Thomas Rossby (U Rhode Island)	C. Flagg (SUNY/SB)	The Norröna Project: An International Collabora-tion for Sustained Studies of the Meridional Overturning Circulation between Denmark, the Faroes and Iceland	NSF	08/2011-07/2015
Irina Rypina (WHOI)	L. Pratt and J. J. Park (WHOI)	Transport Pathways in the North Atlantic: Searching for Throughput	NSF	03/2012-02/2015
R. Saravanan (Texas A&M)	P. Chang (Texas A&M)	Understanding Climate Model Biases in Tropical Atlantic and their Impact on Simulations of Extreme Climate Events	DOE	09/2010-08/2013
Uwe Send (SIO)		Meridional Overturning Variability Experiment (MOVE)	NOAA	2006-Ongoing
C.K. Shum (Ohio State U)	C. Kuo (National Cheng Kung U)	Satellite Monitoring of the Present-Day Evolution of the AMOC	NASA	03/2009-02/2013
Fiamma Straneo (WHOI)	S. Lentz (WHOI)	From Rivers to the Ocean: the Dynamics of Freshwater Export from Hudson Strait	NSF	04/2008-03/2013
Fiamma Straneo (WHOI)	G. Hamilton (U Maine), D. Sutherland (U Washington), L. Stearns (U Kansas)	Glacier-Ocean Coupling in a Large East Greenland Fjord	NSF	08/2009-07/2013
John Toole (WHOI)	M. McCartney, R. Curry and T. Joyce (WHOI), W. Smethie, Jr. (LDEO)	Line W: A Sustained Measurement Program Sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39N	NSF	03/2008-12/2014
Anastasios Tsonis (U Wisconsin; AMOC Lead)	G. Duane (U Colorado; Project PI)	An Interactive Multi-Model for Consensus on Climate Change	DOE	09/2011-08/2013
Eli Tziperman (Harvard U)	D. MacMynowski (CalTech)	Improving Interannual Prediction Skill in a Changing Climate via the Identification of Compensating Coupled Model Errors	DOE	11/2010-10/2013
Chunzai Wang (NOAA/AOML)	D. Enfield (NOAA/AOML)	Relationship of the Atlantic Warm Pools with the Atlantic Meridional Overturning Circulation	NOAA	06/2011-05/2014
Wilbert Weijer (LANL)	M. Maltrud and M. Hecht (LANL), H. Dijkstra and M. Kliphuis (IMAU)	The Sensitivity of the AMOC to Enhanced Greenland Melt Water Input to a Global Eddy-Resolving Ocean Model	DOE	09/2009-08/2012
Joshua Willis (CalTech/JPL)	W. Hobbs (CalTech/JPL)	Monitoring the AMOC Using a Combination of SST, Altimeter and Argo Data	NASA	10/2008-09/2012

Principal Investigator	**Co-PIs**	**Project Title**	**Sponsor**	**Duration**
Xiao-Hai Yan (U Delaware)	Y. H. Jo (U Delaware)	Satellite Multi-Sensor Studies of Deep Ocean Convection in the North Atlantic Ocean	NASA	03/2009-02/2013
Jiayan Yang (WHOI)	L. Pratt (WHOI)	Atmospheric Forcing of Marginal-Sea Overflows	NSF	09/2009-08/2013

APPENDIX 3. Recent AMOC Program publications

Afanasyev, I., S. O'Leary, P. B. Rhines, and E. Lindahl, 2012: On the origin of jets in the ocean. *Geophys. Astrophys. Fluid Dyn.*, **106**, 113-137, doi:10.1080/03091929.2011.562896.

Allan, R., G. Compo, and J. Carton, 2011: Recovery of global surface weather observations for historical reanalyses and international users. *Eos Trans.*, **92**, 154, doi:10.1029/2011EO180008.

Andresen, C. S., F. Straneo, M. H. Ribergaard, A. A. Bjork, T. J. Andersen, A. Kujipers, N. Norgaard-Pedersen, K. H. Kjaer, K. Weckstrom, and A. Alhstrom, 2011: Enhanced calving of Helheim Glacier over the last century forced by the ocean and atmosphere. *Nature Geosci.*, **5**, 37–41, doi:10.1038/ngeo1349.

Azetsu-Scott, K., A. Clarke, K. Falkner, J. Hamilton, E. P. Jones, C. Lee, B. Petrie, S. Prinsenberg, M. Starr, and P. Yeats, 2010: Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea, *J. Geophys. Res.*, **115**, C11021, doi:10.1029/2009JC005917.

Azetsu-Scott, K., B. Petrie, P. Yeats, and C. M. Lee, 2012: Composition and Fluxes of Freshwater through Davis Strait Using Multiple Chemical Tracers, *J. Geophys. Res.*, **117**, C12011, doi:10.1029/2012JC008172.

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APPENDIX 4. Annual AMOC project reports

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

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The oceanographic community has recently agreed that we should work quickly to advance our understanding of the Atlantic Meridional Overturning Circulation (AMOC) in recognition of its importance in Earth's climate system. While intense observational effort has 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. The result is an incomplete description of even the most fundamental characteristics of this exchange flow. This project includes a combined observational and modeling study of the AMOC at the CGFZ. The primary objectives are:

A. to obtain an improved direct estimate of the mean and low frequency variability of the deep westward transport of Iceland-Scotland Overflow Water through the CGFZ, and
B. to gain a better understanding of the causes of the low-frequency variability in the transport of overflow waters through the CGFZ, especially of the role of the NAC in generating this variability.

By providing an improved understanding of the strength and variability of the warm and cold limbs of the AMOC where they cross over the Mid-Atlantic Ridge, we hope to help to sort out the ocean's role in global climate and provide a transport benchmark for critical evaluation of climate models.

Recent Results
An array of eight current meter and hydrographic moorings was installed across the CGFZ in August 2010 to measure the currents and water properties between the bottom and 500 m for two years (see Figure 1 for mooring locations). This array was designed to provide the first long-term, simultaneous observations of both the westward and eastward flows over the CGFZ. An exploratory study of diapycnal mixing intensity in the CGFZ is also included using moored profilers. The array was deployed from the German research vessel *Meteor* as part of a collaboration with Dr. Monika Rhein (University of Bremen) on deep and intermediate currents crossing the mid-Atlantic ridge near the CGFZ.

During July 2012, all eight of the WHOI CGFZ moorings were successfully recovered by WHOI technicians from the German research vessel Merian (Dr. Dagmar Kieke, chief scientist), on a cruise from Reykjavik to Nuuk. A preliminary look at the data shows quite good performance of the three moored profilers, 36 microcats and 28 current meters. Data processing is underway for all instruments. We are grateful to Drs. Monika Rhein and Dagmar Kieke for securing ship time for the mooring recovery. WHOI technicians also assisted with German mooring operations during the 30-day cruise.

Modeling work has concentrated on idealized configurations of both primitive equation and quasigeostrophic models of the circulation induced by flow impinging on ridges and islands with gaps. Focus has been on the local and remote influences of the topography on the mean circulation. Meridional ridges within a wind-driven gyre system have been found to influence the strength and structure of recirculation gyres to the west of the ridge as well as the pathway of the separated boundary current. If the topography extends all the way to the surface, the interaction of the Ekman transport with an island causes narrow regions of upwelling/downwelling along the island boundary, as well as deformation scale thermal anomalies and boundary currents. The three-dimensional structure is complex, with a phase rotation with depth of density, pressure, and velocity fields. Topography provides dynamical "highways" that connect regions of downwelling to regions of upwelling, and transmit the surface Ekman transport from one side of the island chain to the other.

As part of the broader impact activities associated with this project, Bower recently hosted another field trip to WHOI by Perkins School students and staff, which included short collection trips on a local charter vessel and a demonstration of a science fair project on the impact of ocean acidification on hermit crab feeding by a Falmouth High School student. Bower also gave keynote talks on oceanography and being a visually impaired scientist at the National Library Service for the Blind and Physically Handicapped Annual Convention in Newport, Rhode Island, and at the Massachusetts Commission for the Blind Internship Closing Ceremonies in Boston, Massachusetts.

Project updates are posted at http://www.whoi.edu/scientist/abower.

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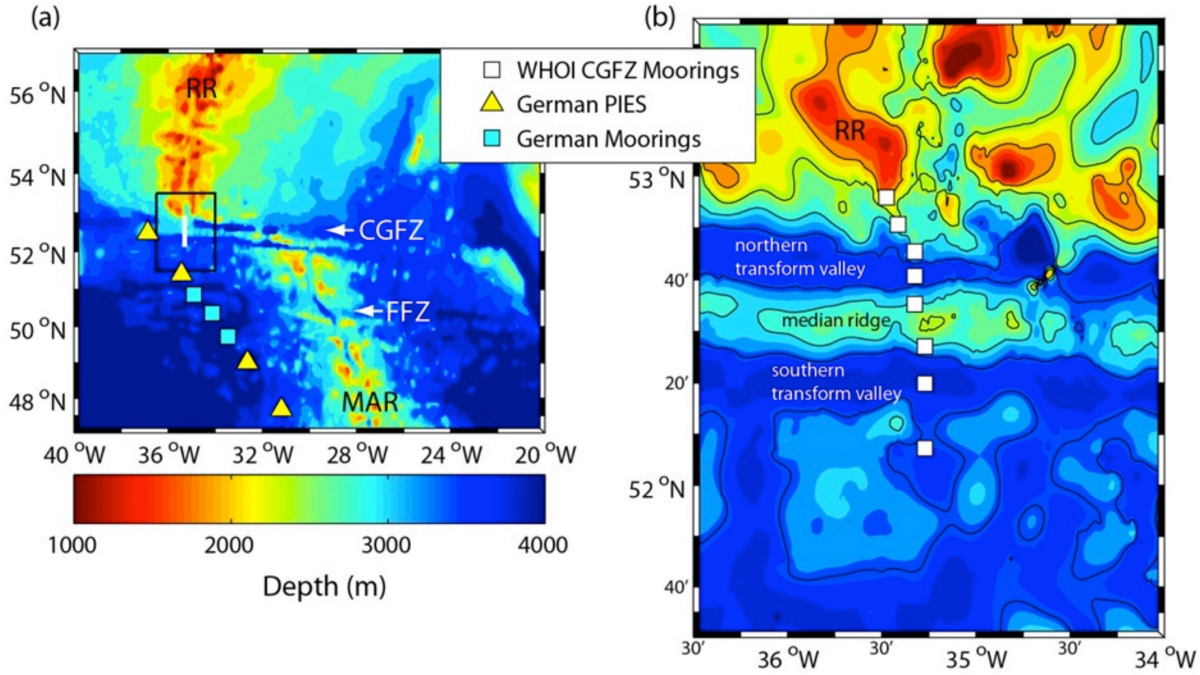

Figure 1. (a) Bathymetry of Reykjanes Ridge (RR) and Charlie-Gibbs Fracture Zone (CGFZ), with locations of the WHOI moored array (bold white line) and German moored array. MAR – Mid-Atlantic Ridge; FFZ – Faraday Fracture Zone. (b) Expanded view of the boxed area in (a), using high-resolution (30 arc second) bathymetry. Positions of WHOI moorings are shown by squares. The 2000, 2500, 3000 and 3500-m isobaths are highlighted by black contour lines.

Role of Atmospheric Internal Variability in the Atlantic Meridional Overturning Circulation

PI: Ping Chang, Texas A&M University
Co-PI: Ben Kirtman, University of Miami

Objectives: The objectives of this research are two-fold: 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.

Since the start of the project in September 2011, we have completed a major portion of the proposed research that involves testing the two scientific hypotheses:

1) AIV through its effect on ocean mixing and deep-water formation processes plays a key role in AMOC variability as well as in maintaining its mean strength;
2) AIV changes in response to global warming may contribute significantly to projected AMOC changes under global warming scenarios.

Findings: We have conducted an interactive-ensemble (IE) CCSM3 simulation and a set of POP2 ocean-sea ice coupled model simulations to test the two scientific hypotheses. The results show that internally generated high-frequency, synoptic-scale weather variability in the atmosphere plays a significant role in maintaining the overall strength and variability of the AMOC that affects climate variability and change. We conjecture that the intensified Atlantic storm track activity during the 20th century may have exerted a strong influence on AMOC's long-term trend variability by counteracting the effect due to subpolar ocean surface buoyancy increase in response to global warming. Thus, interactions between storm tracks and AMOC may be an important feedback mechanism of the global climate system and need to be taken into consideration in climate change studies. The results have written as a paper submitted to *Nature Climate Change*.

Publication:

Wan, X., and P. Chang, et al. 2013: Weather's Effect on Atlantic Meridional Overturning Circulation and Climate Change, *Nature Climate Change*, submitted.

Assessing the Atlantic Meridional Overturning Circulation (AMOC) in Climate Models

PIs: Wei Cheng, Dongxiao Zhang
University of Washington/JISAO and NOAA/PMEL

The objective of this research is to examine the AMOC amplitude and temporal variability simulated by the Coupled Model Intercomparison Project phase 5 (CMIP5) models, and compare them with CMIP3 results and observations. This was part of the RAPID (Rapid Response Research) initiative on analysis of climate model simulations for the IPCC AR5 report.

Results

We examined the AMOC simulated by CMIP5 models in historical (1850-2005) and future climate. The available output, from ten models thus far, indicates historical simulations more closely matched to observations than those of the CMIP3. Similar to CMIP3, all models predict a weakening of AMOC in the 21st century, and the degree of weakening varies considerably between models. In the RCP4.5 scenario, the weakening by the end of 21st century is 5%–40% of individual model's historical mean state; under RCP8.5, the weakening increases to 15%–

60% over the same period. RCP4.5 leads to stabilization of AMOC in the second half of the 21st century, and a slower (than weakening rate) but steady recovery thereafter, while RCP8.5 gives rise to a continuous weakening of AMOC in the entire span of 21st century.

In the CMIP5 historical simulations, all but one model exhibit a weak downward trend (ranges from –0.1 to –1.8 Sv/century) over the 20th century. On top of this weakening trend, the multi-model ensemble mean AMOC exhibits multidecadal variability with a ~60-year periodicity and peak-to-peak amplitude of ~1 Sv; all individual models project consistently onto this multidecadal mode. This multidecadal variability is significantly correlated with similar variations in surface net shortwave radiative flux, but with a ~10-year phase lag.

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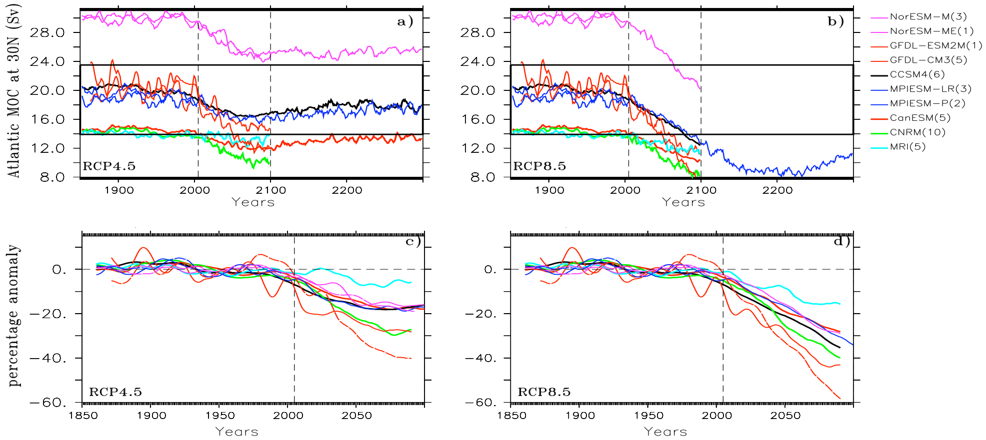

Figure 1. "AMOC index" at 30°N (units: Sv). Model names and ensemble numbers (in the brackets) are listed. The time series was averaged over each model's ensemble runs. Top: absolute values of the AMOC index. The observed AMOC by the first four years of RAPID data, 18.7±4.8 Sv, is marked by the horizontal lines. Bottom panels: percentage change in AMOC index relative to each model's ""historical" mean.

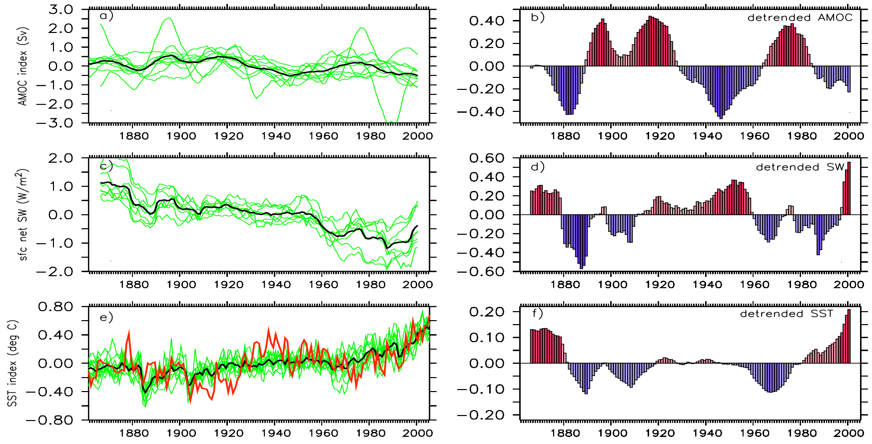

Figure 2. Climate indices in the North Atlantic: anomalous AMOC index (top row), surface net shortwave radiation (middle row), and SST (bottom row). Left panels: from individual models (green lines) and from the multi-model ensemble mean (black line). Right panels: linear detrended multi-model ensemble mean indices. Red line in e) is the corresponding SST anomalies from ERSST data set.

High-Resolution Model Development to Quantify the Impact of Icebergs on the Stability of the Atlantic Meridional Overturning Circulation

PIs: A. Condron and R. Bradley
Climate System Research Center, University of Massachusetts Amherst, MA, USA

The aim of this project is to understand the sensitivity of the Atlantic Meridional Overturning Circulation (MOC) to changes in the hydrological cycle at high latitudes. Most runoff from the large continental ice sheets of Greenland and Antarctica occurs as icebergs (66 % for the Greenland Ice Sheet) focused into narrow fjords. These icebergs can drift many thousands of kilometers from their source before finally melting. This project is designed to develop a sophisticated, thermodynamic, iceberg model to more accurately simulate the delivery of freshwater from the major continental ice sheets of Greenland and Antarctic to the open ocean convection regions in the ocean during both glacial and modern-day periods to understand the sensitivity of the MOC to freshwater forcing.

Recent Results

Our state-of-the-art thermodynamic iceberg model now incorporates many of the most recent developments in iceberg physics that are used in the latest Operational Iceberg Forecast models (Figure 1a). The model also considers: grounding, iceberg stability, surface albedo changes, collisions, and calving. A comparison between the trajectories of icebergs simulated by our model with observations derived from GPS instruments dropped onto individual icebergs is showing encouraging results. We have also developed a high resolution (1/6°; 18-km) North Atlantic-Arctic regional ocean sea-ice model (based on MITgcm) to understand the sensitivity of the MOC to freshwater released from icebergs during the Last Glacial Maximum (LGM; 21,000 yrs BP; Figure 1b). In contrast to modern-day climate models, the vast majority of paleoclimate simulations are still run at spatial resolutions that are insufficient (~2°) to accurately determine ocean circulation, vertical water column structure, and the sensitivity of the MOC to freshwater forcing. However, during glacial periods, large 'armadas' of icebergs traversed the North Atlantic and released exceptionally large amounts of fresh water to the North Atlantic, making this period ideal for unraveling the sensitivity of the MOC to freshwater forcing. Significant findings so far include:

- Approximately 80% of the total volume of freshwater runoff from Greenland is released more than 200-km offshore of the Greenland coast.
- Icebergs are primarily confined to the coastal boundary currents of the North Atlantic when the ocean is simulated at high resolution. We see very little penetration of icebergs into the central Greenland and Labrador Seas where deep convection is thought to play a key role in the moderating the strength of the MOC.
- During the Last Glacial Maximum, the Arctic was covered by sea ice year round. The Nordic seas were ice covered in the winter south to the latitude of the Faeroe Isles, and ice free east of Jan Mayen Island in the summer. Icebergs penetrated significantly further south than today.

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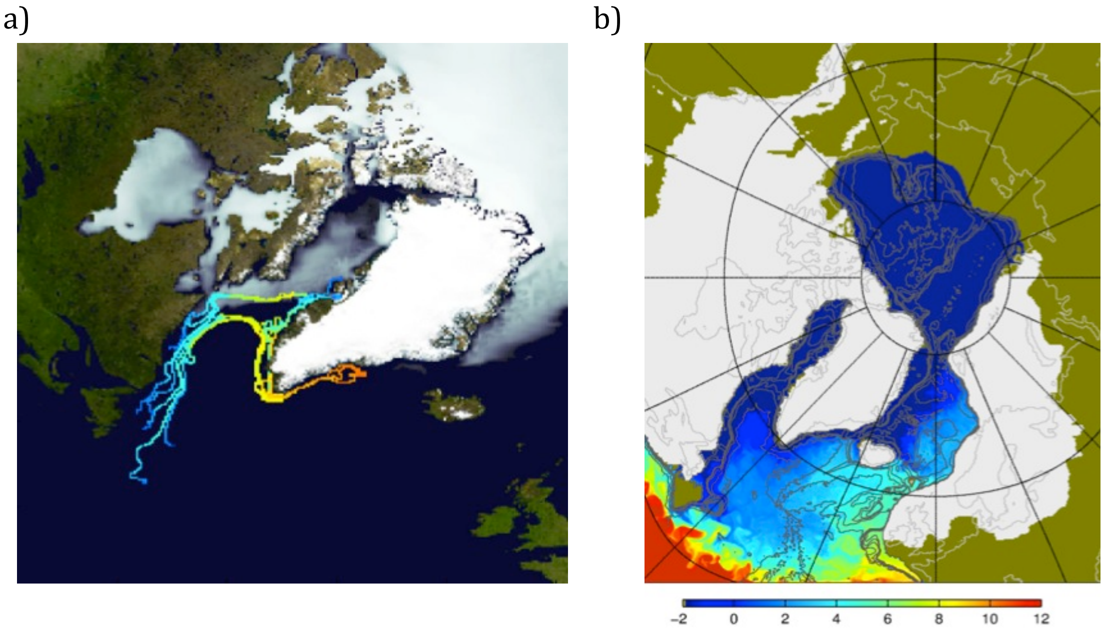

Figure 1. a) The trajectories of icebergs calved from the Greenland Ice Sheet. The colors along the individual paths refer to the size of the icebergs, with yellow/orange referring to larger icebergs. The iceberg model is coupled to MITgcm ocean sea-ice model integrated at 1/6°. b) Our model (based on MITgcm) configured to simulate the circulation of the ocean and sea ice during the Last Glacial Maximum (LGM) at 1/6° resolution. The colorbar shows sea surface temperature (from -2° to 12° C), while the green color highlights land above sea-level and white areas depict the large continental ice sheets that covered North America (Laurentide Ice Sheet) and Europe (Eurasian Ice Sheet) at this time.

A Collaborative Investigation of the Mechanisms, Predictability, and Climate Impacts of Decadal-Scale AMOC Variability Simulated in a Hierarchy of Models

NCAR PIs: G. Danabasoglu and J. Tribbia
NCAR Collaborators: S. Yeager and A. Karspeck
National Center for Atmospheric Research (NCAR), Boulder, CO

In this collaborative effort between NCAR, GFDL, and MIT, we seek to advance our understanding of AMOC by comparing and contrasting its variability mechanisms, surface climate impacts, and predictability obtained in a diverse set of models, from simple delayed oscillators to idealized basin models to full-complexity IPCC-class coupled general circulation models. Here, we highlight some recent results from the NCAR group.

Recent Results
We are analyzing the AMOC mean state and variability in a set of 18 ocean – sea-ice hindcast simulations for the 1948-2007 period which have been run by 15 modeling groups around the world. These simulations are the second in a series of planned Coordinated Ocean-Ice Reference Experiments (COREII) organized by the CLIVAR Working Group on Ocean Model Development (WGOMD). The analysis of these nearly identically-forced model simulations will test the hypothesis that models generate the same AMOC mean and variability when subject to the same interannually-varying forcing. Preliminary results show that indeed, most of the models – in fact, *all* of the models which are able to simulate deep convection in the Labrador

Sea – have a dominant AMOC EOF1 (Empirical Orthogonal Function) which indicates there was a large-scale spin-up of AMOC between about 1970 and 2000. There is a similar agreement on driving mechanism, with most models showing that enhanced deep convection in the Labrador Sea preceded the decadal AMOC changes. This multi-model result lends support to the argument of Yeager et al. (2012), that the source of the significant North Atlantic prediction skill in the NCAR decadal prediction system comes from accurate initialization of a slow spin-up of the AMOC which occurred over the latter half of the 20th century.

The mechanisms of historical AMOC variability have been closely examined in the NCAR model, and the findings should be general enough to explain the common variability of the COREII multi-model comparison. Sensitivity experiments have been run to determine the relative importance of momentum vs. buoyancy forcing in driving the long-term AMOC changes seen in COREII simulations (Fig. 1). The CONTROL run is the 60-year COREII hindcast simulation using the ocean component of the Community Earth System Model (CESM). This is compared to a sensitivity run forced with interannually-varying momentum forcing but with a repeating annual cycle of buoyancy forcing (MOM), and another sensitivity run which is forced with interannually-varying buoyancy forcing but with a repeating annual cycle of momentum forcing (BUOY). The sum of MOM and BUOY anomalies (MOM+BUOY) largely reproduces CONTROL. It is evident from this analysis of the NCAR COREII simulation that the upward trend in AMOC transport is predominately driven by buoyancy forcing, while momentum fluxes contribute primarily to interannual and high frequency fluctuations of the AMOC. The buoyancy-driven decadal AMOC changes apparently emanate from the Labrador Sea and subsequently propagate southwards. The genesis of these anomalies in the high latitudes coincides with extreme outbreaks of cold, dry air, as indicated by the black circles in Fig. 1.

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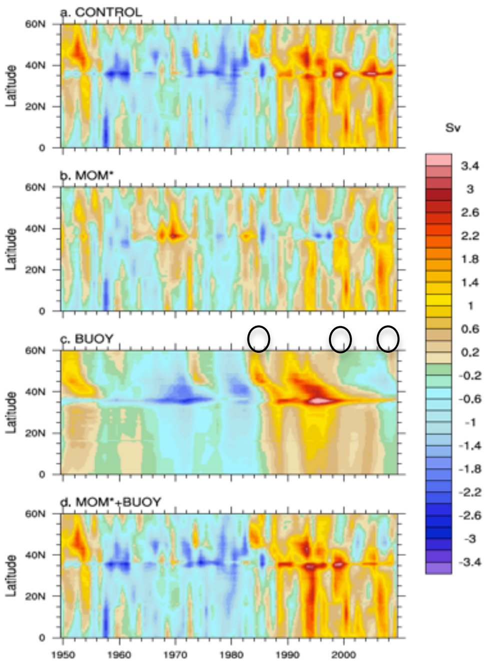

Figure 1. AMOC transport anomaly as a function of time and latitude: a) NCAR COREII hindcast simulation (CONTROL), b) interannual momentum flux simulation (MOM), c) interannual buoyancy flux simulation (BUOY), and d) MOM+BUOY. The circles in c) indicate winters when the cold air outbreaks were active in the Labrador Sea region.

A Collaborative Investigation of the Mechanisms, Predictability, and Climate Impacts of Decadal-Scale AMOC Variability Simulated in a Hierarchy of Models

GFDL PIs: T. Delworth[1], A. Rosati[1,]
in collaboration with investigators G. Danabasoglu[2], lead and J. Marshall[3], lead
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[2]NCAR/UCAR Boulder, CO USA
[3]MIT, Cambridge, MA, USA

The objectives of this collaborative project are: (i) to better understand the mechanisms of AMOC variability and predictability, (ii) to understand the impact that AMOC variability has on climate over both oceanic and continental regions, and (ii) to develop a decadal prediction system for the AMOC, and to conduct experimental decadal AMOC predictions. The primary method is to use a hierarchy of models to characterize simulated AMOC variability, to diagnose mechanisms of that variability, and to assess decadal predictability, especially of the AMOC.

Recent Results

An extensive suite of decadal-scale hindcasts has been completed using the GFDL CM2.1 coupled climate model (Rosati et al. submitted). Specifically, for each year from 1961-2012, a ten-member ensemble of decadal-scale predictions was initiated on 1 January of each year. For these experiments the model was initialized with observations based on January 1 of that year, and each ensemble member was integrated forward in time for 10 years. In addition, a ten-member ensemble of experiments was conducted with the same model but without initialization of the model with observations. Thus, differences in the ensembles represent the impact of initialization on decadal scale predictive skill. Model results are available at http://nomads.gfdl.noaa.gov:8080/DataPortal/cmip5.jsp.

On the decadal scale most of the predictive skill for near-surface temperatures is associated with radiative forcing changes. However, for the North Atlantic there is an additional source of predictive skill that comes from model initialization. The decadal scale predictive skill comes from prediction of aspects of Atlantic Multidecadal Variability and ocean circulation changes related to the AMOC (Yang et al. in press; Msadek et al. in preparation). Using a technique that extracts the most predictable pattern, the model shows some predictive skill for a pattern of North Atlantic SST anomalies, with the dynamical model showing more skill than persistence for lead times up to 7 years.

Additional work has examined the AMOC simulation and variability characteristics in a new generation of high-resolution coupled climate models developed at GFDL (Delworth et al. 2012). These models have ocean resolution that can be characterized as either eddy-permitting or eddy-resolving. This is complementary to additional analyses of AMOC variability in the GFDL CM2.1 model, which shows pronounced interdecadal and multi-centennial timescales of AMOC variability.

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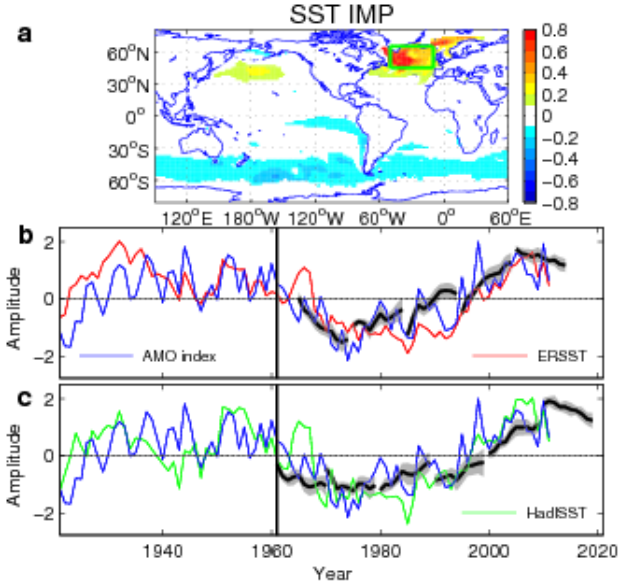

Fig. 1. (from Yang et al. 2013) **a**, The spatial structure of the component that maximized the average predictability time of SST in the decadal hindcasts, which is called IMP. **b**, The ensemble mean (black solid) and spread (gray shading) time series of IMP as a function of forecast lead time for the decadal hindcasts initialized on 1 January every 10 years from 1965 to 2005, the time series for projecting the ERSST data onto IMP (red solid) and the normalized AMO index (blue solid) from 1920 to 2010. **c**, Same as **b** but for hindcasts initialized on 1 January 1961 and every 10 years from 1970 to 2010. The green line denotes the projected time series of HadISST data onto IMP.

Assessing the Sensitivity of Northward Heat Transport/Atlantic Meridional Overturning Circulation to Forcing in Existing Numerical Model Simulations

PIs: Shenfu Dong[1,2], Gustavo Goni[2], Molly Baringer[2], and Geroge Halliwell[2]
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[2]NOAA/AOML

This project is to examine the MOC and MHT estimates from observations and using those observation-based estimates to evaluate the performance of climate models in reproducing the MOC/MHT temporal and spatial variability. Using nearly 10 years of high-density XBT transects (AX18), we found that the mean MOC and MHT at 34°S are 18 Sv and 0.55 PW, respectively (Dong et al. 2009; Garzoli et al. 2012). Detailed analysis of transport estimates from AX18 (Dong et al. 2009, 2011) indentified differences between model simulations and observations in a variety of aspects. Dong et al. (2009) showed that both the boundary currents and the interior flow contribute significantly to the variability of the South Atlantic MOC. Therefore, to adequately measure the South Atlantic MOC changes, it is important to monitor all three regions. In an effort to examine the performance of climate models, Dong et al. (2011) found that the IPCC-AR4 models are unable to capture the mean and variability of the boundary currents in the South Atlantic, particularly in the eastern boundary (Figure 1).

Our recent study using observations from Argo profiling floats and from GFDL models found that the MOC from model T/S fields show strong transport in the ocean interior region compared to the MOC estimated from Argo T/S fields. The geostrophic component of the MOC estimated from Argo data shows a seasonal variation with the maximum value in January and minimum value in August (Figure 2). However, the seasonal variations of the geostrophic contributions to the MOC from model T/S fields is very weak. Examination of the density field suggests that the difference may be related to the vertical coherent density variations in the Argo measurements, which is not shown in the model field. The biases in model wind stress curl can also explain the seasonal differences seen between observations and models.

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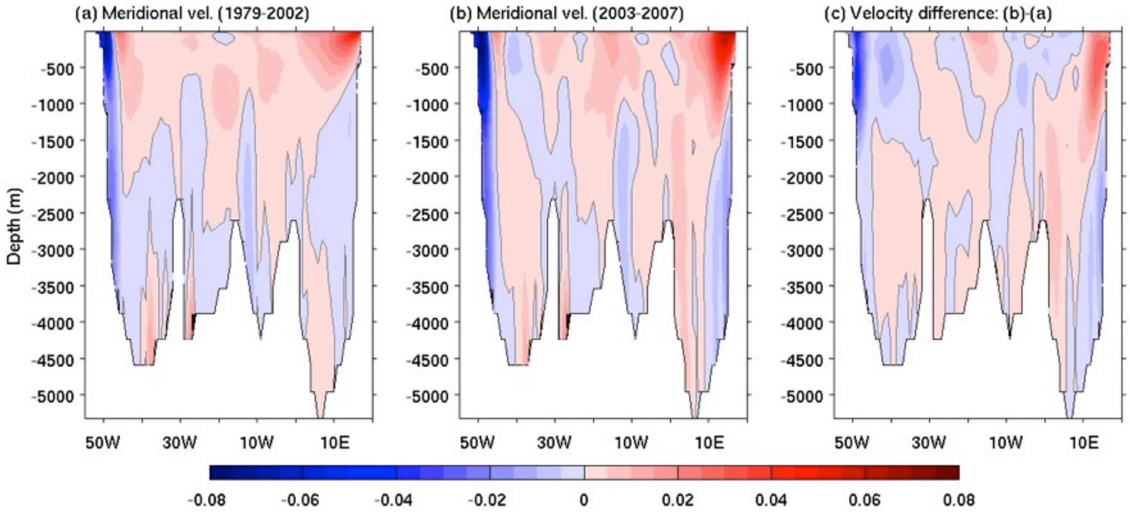

Figure 1. Meridional velocity from GFDL CDA averaged (a) during 1979-2002, (b) during 2003-2007, and differences in averaged meridional velocity for the two periods, 2003-2007 and 1979-2002. Unit is $m\ s^{-1}$.

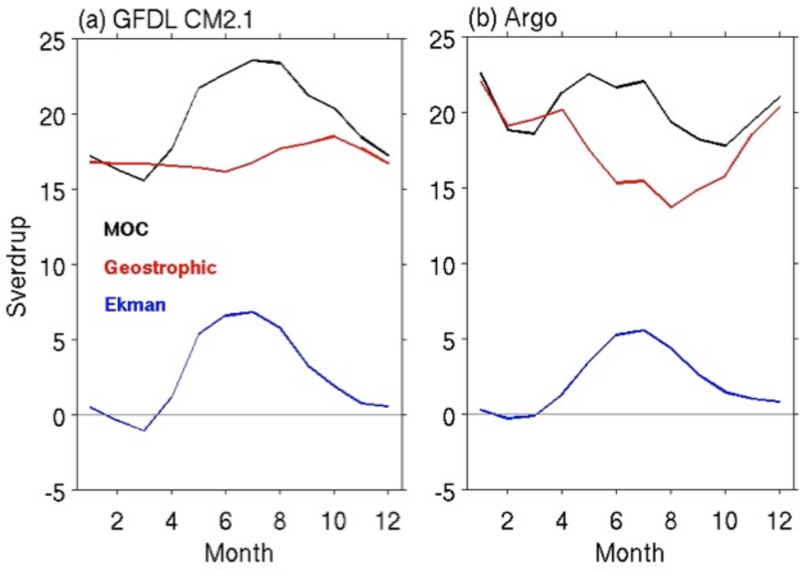

Figure 2. Estimates of MOC (black) and it contributions from geostrophic (red) and Ekman (blue) components based on temperature and salinity climatology constructed from GFDL CM2.1 (b).

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

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[2]School of Marine and Atmospheric Science, 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 a monthly XBT sections. The XBT program, operated by the National Marine Fisheries Service has been in continuous operation since 1977.

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 XTB temperature measurement program in collaboration with NOAA/NMFSC; 3) to provide near-real-time processed data distribution to enable broad community participation in scientific analysis; 4) to investigate the linkages between these oceanographic regimes and their connections to large-scale forcing fields.

Through collaboration with Lisa Beal and the University of Miami's Explorer of the Seas program we have been studying the capabilities of the 38 kHz ADCPs, which have the potential of doubling the profiling depth of our current 75 kHz unit deployed on the Oleander. As a result of that effort we found two transects that slice right through the centers of an anticyclonic eddy in the Sargasso Sea well east and a second cyclonic eddy just south of the Gulf Stream off Cape Hatteras. The results of that study, A tale of two eddies: diagnosing eddies through acoustic remote sensing (JGR, 2011, doi:10.1029/2011JC007307) by Rossby, Flagg, Ortner and Hu, showed well-resolved deep eddies with very high relative vorticities (almost -f for the anticyclone and > +f for the cold core ring) with major displacement and alteration of the deep scattering layer. By integrating the momentum equation the radial-vertical geopotential anomaly field of the eddies could be determined, and hence also their potential energy. This means that the kinetic and potential energy of the eddies can be determined purely through acoustic remote sensing. An interesting feature of the anticyclonic eddy was that satellite data showed that it was one of a vortex pair that had formed offshore of the Gulf Stream and which seemed to have self-propagated some 500 km eastward; part of the time quite rapidly.

Previous investigators have shown that the North Atlantic Oscillation, the Southern Oscillation Index and the Icelandic Low are related to the Gulf Stream North Wall with 2 or 3 year lags, Sanchez Franks (Stony Brook PhD study in progress) has developed a multiple linear regression method to forecast the Gulf Stream North Wall one year in advance. These results also provide support for the influx of Labrador Sea Water as the driving mechanism behind the Gulf Stream's north-south migration. However, it is still unclear why the longitude of the Icelandic low also plays a significant role, and why there exists a 2-3 year lag between the atmospheric perturbations and the Gulf Stream North Wall migration.

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

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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. The generalized stability analysis uses tangent linear models in conjunction with their adjoints to determine a variety of characteristics of ocean circulation and variability. Using this method, by calculating the AMOC optimal perturbations for example, we can assess the sensitivity of this circulation to perturbations and explore the possibility of rapid changes in the system. In additions, we can also calculate optimal steady and finite-time perturbations in surface heat and freshwater fluxes that affect the AMOC the strongest, which is essential for understanding the AMOC response to climate change. We can also extract the leading internal modes of the AMOC associated with ocean dynamics and study their properties.

Recent Results

We have applied this method to a realistic ocean general circulation model (NEMO-OPA) to show rigorously the existence in the system of a weakly-damped mode of oscillation centered in the North Atlantic and related solely to the dynamics of the AMOC (Sevellec and Fedorov 2013a). In this particular GCM the mode period is roughly 24 years, its e-folding decay timescale is 40 years, and it is the least damped oscillatory mode in the system (Figure 1). The mode mechanism is related to the westward propagation of large-scale temperature anomalies in the northern Atlantic in the latitudinal band between 30 and 60N. The westward propagation results from of a competition between mean eastward zonal advection, equivalent anomalous westward advection due to the mean meridional temperature gradient, and westward propagation typical of long baroclinic Rossby waves. The zonal structure of temperature anomalies alternates between a dipole (corresponding to an anomalous AMOC) and anomalies of one sign (yielding no changes in the AMOC). An idealized model has been formulated to highlight the importance of the strong background meridional temperature gradient in the North Atlantic for the oscillatory mechanism of this mode.

Further, we have shown that the most efficient way to excite this interdecadal AMOC mode is via optimal initial perturbations in surface temperature and salinity centered off the east coast of Greenland and Canada, south of the Denmark Strait (Sevellec and Fedorov 2013b). Simple estimates indicate that realistic variations in SST or surface salinity in this region can induce variations in the AMOC volume transport on the order of 20%. Finally, we have also applied this method to study the limits of decadal predictability related to ocean dynamics (Sevellec and Fedorov 2013c).

The main manuscripts are available online:
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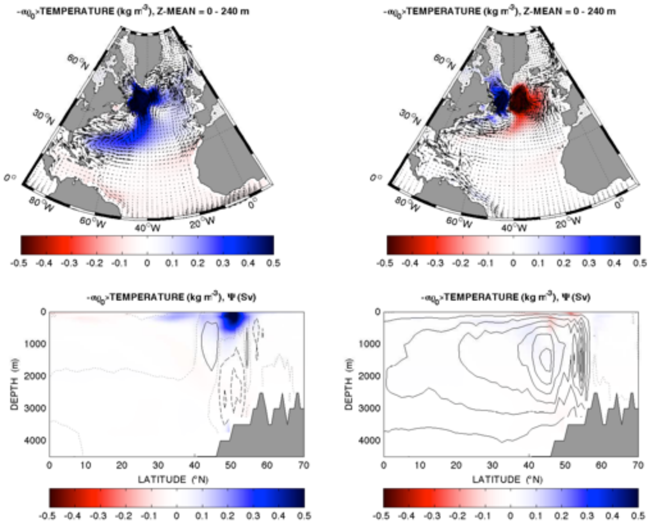

Figure 1. The spatial structure of the dominant oscillatory AMOC mode in a realistic ocean GCM (OPA): anomalies in (top) upper-ocean temperature and surface currents and (bottom) meridional streamfuction and zonally-averaged temperature for two phases of the oscillation separated by a quarter-period (left and right columns, respectively). Temperature variations are given in terms of density. The ocean fields in the left and right columns are separated by roughly a 6-year interval. The full period of the mode is 24 years. After Sevellec and Fedorov 2013a.

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

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The objectives of this project are to use a combination of historical data, profiling Argo floats, satellite data, and modeling tools to evaluate oceanic heat storage in the high-latitude Southern Ocean and to assess oceanic transport of heat poleward toward the Antarctic continent. The project has focused on the Pacific Ocean basin, because the most rapid melting of the Antarctic continent has been reported near Pine Island Glacier in the southeastern Pacific Ocean. Our approach has been multi-pronged, with separate analyses focused on the tropical to mid-latitude Pacific, the Antarctic Circumpolar Current (ACC), and the region around the Antarctic ice shelves.

Recent results

(1) Meridional overturning circulation in the tropical Pacific has been evaluated from a combination of Argo floats, reanalysis fields, and satellite altimetry (Zilberman et al. 2012). The methodology has been extended to evaluate meridional transport toward the Antarctic continent at 32S. Transport within the top 2000 meters from Argo is strongly correlated with surface transport estimated from satellite altimetry, indicating strong vertical coherence in the transport variability. Results show that during the Argo time period (from about 2004 to present) meridional transport is correlated with the Southern Annular Mode (SAM) but not with changes in El Niño and the Southern Oscillation (ENSO), as measured by the Niño 3.4 index. The total transport can be broken into two parts: the transport in the western boundary current (the East Australia Current) is anti-correlated with the SAM, while transport to the east of the EAC, which is primarily controlled by the northward recirculation of the EAC is positively correlated with the SAM.

(2) One of the challenges in assessing meridional transport in the ocean is to determine whether narrow jet-like western boundary currents are adequately resolved by the Argo float sampling program. For the East Australia Current, transport estimates from high-resolution in situ observations have been assessed relative to transport estimates from Argo. Results show that Argo does provide a good measure of western boundary current variability. Future plans will involve extending these findings to include all five major western boundary currents of the global ocean, and this will be of direct relevance for the AMOC program.

(3) South of the ACC at Pine Island Glacier, in situ ocean data are sparse, but available observations of the glacier suggest a rapidly changing ocean might contribute to basal melting of the ice shelf and might ultimately destabilize the continental ice. A data-assimilating ocean model, the Southern Ocean State Estimate (SOSE), has been used to evaluate the mechanisms governing heat transport across the Antarctic continental shelf into Pine Island Bay. The model analysis supports the idea that heat advection is the predominant source of heat to the region, and suggest that changes in lateral advection into the Pine Island Bay region are controlled by local changes in wind-stress curl.

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

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An overarching goal of the project is to describe and understand the three-dimensional time-evolving structure of the ocean circulation in the Atlantic, from dynamically and kinematically consistent state estimates that have been constrained by most of the available oceanic observations covering the period 1992 to present.

Recent Results

A new-generation ECCO sustained production calculation (ECCO-Production) version (ECCO-GODAE follow-on), which is currently being developed, has been scrutinized in terms of circulation variability in the Atlantic. Meridional volume, enthalpy, and freshwater trans- ports are being assessed at various latitudes (Forget et al. in prep.; Wunsch and Heimbach 2012b). At 26N, where the RAPID/MOCHA array exists, the meridional volume transport exhibits large month-to-month variability (Figure 1), an aspect already pointed out by Wunsch and Heimbach (2006) and later confirmed by Cunningham et al. (2007). No data from RAPID/MOCHA have been used so far in the ECCO-Production estimation procedure, which have been added to the figure as independent estimates (red curves). Note that the ECCO-Production estimate reaches back to 1992, showing no discernible trend over that period. It enables a wide range of basin (or global) scale analyses, such as those by Piecuch and Ponte (2012). Other examples, completed or in progress, include assessment to which degree Sverdrup balance provides an adequate description of the Atlantic circulation (Wunsch 2011), inference of patterns of wind power input on regional and global scales (Roquet et al. 2011), or the assessment of meridional coherence of volume transports which exhibits decorrelation across 40N and again 60N (Wunsch and Heimbach, 2012a).

Work has continued using both statistical methods (Wunsch, 2012) as well as coupled tangent linear and adjoint versions of the MITgcm to compute singular vectors for climatically relevant norms, such as Atlantic MOC or upper-ocean heat content (Zanna et al., 2012). Both studies suggest limits of linear predictability of the AMOC to be significantly less than a decade. The latter study, in particular, demonstrates that optimal perturbation patterns and associated time scales differ, depending on whether those perturbations are restricted to the upper ocean or are allowed to extend over the entire water column. Further analyses by Wunsch and Heimbach (2012a) suggest that the AMOC exhibits a stationary Gaussian weak red-noise behavior. The system is subject to continuous stochastic disturbances by external processes (winds, precipitation, etc.) which themselves are decorrelated in time and space and to internal instabilities of a wide assortment. As a zonal integral through the large variety of physical processes in the three-dimensional ocean circulation, understanding of the AMOC, if it is of central climate importance, requires breaking it down into its unintegrated components.

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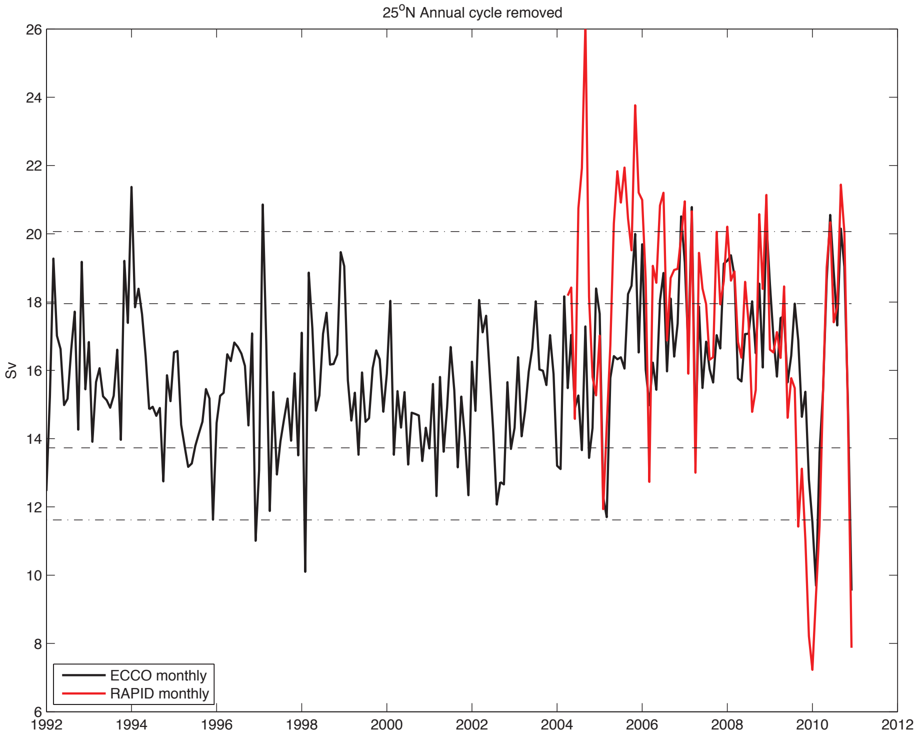

Figure 1. Monthly maximum meridional volume transport at 25^{o}N from a preliminary solution of the forthcoming ECCO-Production (ECCO-GODAE follow-on) version 4 estimate (black curve), and the RAPID/MOCHA estimate (red curve). An annual cycle and higher harmonics have been removed. Dashed lines indicate the 1-sigma and 2-sigma levels.

Bering Strait and the AMOC under glacial-interglacial climate

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The objective of this program is to study the impact of the Bering Strait througflow in the AMOC hysteresis and global climate under glacial and interglacial climate conditions.

Recent Results

Abrupt climate transitions, known as Dansgaard-Oeschger and Heinrich events, occurred frequently during the last glacial period, specifically from 80 – 11 thousand years before present, but were nearly absent during interglacial periods and the early stages of glacial periods, when major ice-sheets were still forming. Here we show, with a fully coupled state-of-the-art climate model, that closing the Bering Strait and preventing its throughflow between the Pacific and Arctic Oceans during the glacial period can lead to the emergence of stronger hysteresis behavior of the ocean conveyor belt circulation to create conditions that are conducive to triggering abrupt climate transitions. Hence, it is argued that even for greenhouse warming, abrupt climate transitions similar to those in the last glacial time are unlikely to occur as the Bering Strait remains open.

Paleo proxy data and previous modeling studies both indicate that the massive discharge of icebergs into the North Atlantic may have led to a (nearly) collapsed Atlantic meridional overturning circulation (AMOC), resulting in a seesaw-like climate change between the North Pacific and North Atlantic, with a warming in the former and a cooling in the latter. Here by using a fully coupled climate model, we show that this Pacific-Atlantic seesaw associated with changes of the AMOC can only occur when the Bering Strait is closed. As this strait is closed, the oceanic communication between the North Pacific and Atlantic is cut off. When AMOC collapses, the North Atlantic becomes cooler, but the North Pacific becomes warmer due to the buildup of the Pacific meridional overturning circulation which transports more warm and salty subtropical water into the North Pacific, leading to seesaw-like climate changes in the two ocean basins.

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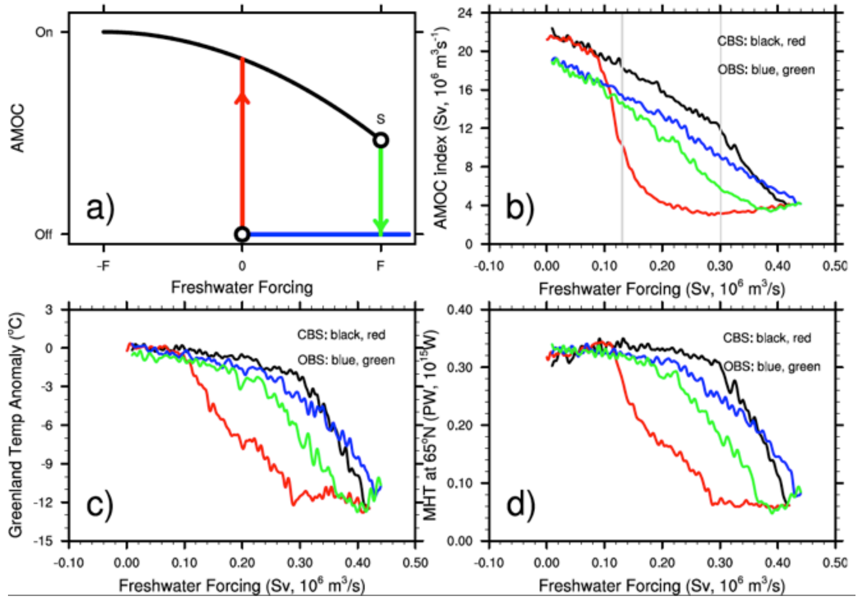

Figure 1. Theoretical and simulated AMOC hysteresis curves (a, b) and the associated changes of Greenland surface temperature and meridional heat transport at 65°N in the Atlantic (c, d). In panel a), "S" is the bifurcation point beyond which AMOC collapses and the "+/-F" values indicate the freshwater forcing strength. In panels b), c), and d), the black/red (blue/green) lines are for the closed (open) BS simulation. The black/blue (red/green) lines represent the phase of freshwater forcing increase (decrease) in these simulations. Note that a change of the freshwater forcing by 0.1 Sv (Sv$\equiv10^6$m^{3}s^{-1}) in this figure takes place over 500 model years.

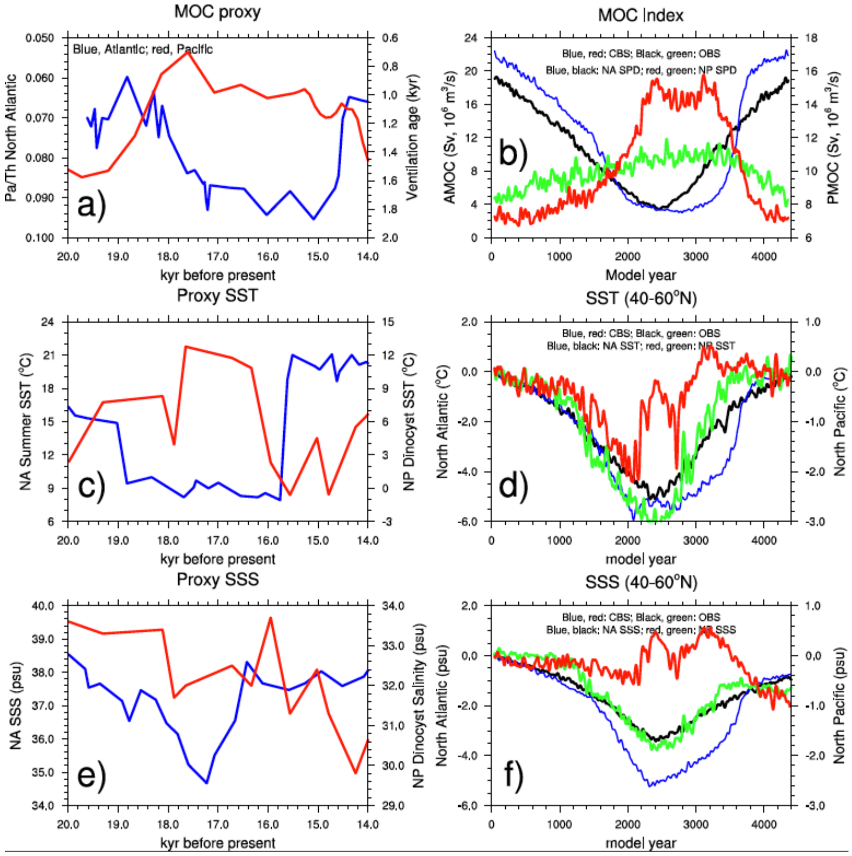

Figure 2. Proxies for AMOC (Ph/Th, blue line; McManus et al., 2004) and PMOC (ventilation age based on ^{14}C, red line; Okazaki et al., 2010) during Heinrich 1 event, both axes oriented such that stronger MOC plotted towards the top of the chart (a). North Atlantic and North Pacific sea surface temperature from foram (Waelbroeck et al., 2001) and dinocyst assemblages (deVernal and Pedersen, 1997) (c), and sea surface salinity from foram assemblages and d^{18}O (Chapman and Maslin, 1999) and dinocyst assemblages (deVernal and Pedersen, 1997)(e). Time evolving AMOC, PMOC (b), sea surface temperature (d) and salinity (f) of the North Pacific and North Atlantic basins between 40 and 60^{o}N from our model.

An Observing System for the Meridional Overturning Circulation and Ocean Heat Transport in the Subtropical North Atlantic

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[4]Scottish Marine Institute Oban, Argyll, U.K.

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 26.5º N using a basin-wide observing system. As of December 2010 we had 6.7 years of data in hand from the full trans-basin array. With current funding the array will be maintained through 2014.

Recent Results

The mean values for the AMOC strength and northward heat transport from the time series collected thus far, from 2004-2010, are 17.5 Sv and 1.28 PW, respectively. Year-to-year variability was relatively small during the first five years of the time series, but a large anomaly in both the AMOC and heat transport occurred in 2009-2010, resulting in lower mean heat transports of about 1.1 PW during those years. This anomaly was driven in part by reduced Ekman transports associated with a strong negative NAO anomaly in winter 2009-2010 - which recurred again in winter 2010-2011 - and in part by changes in the western boundary current and mid-ocean transports. A significant cooling event also occurred in the mid-latitude North Atlantic starting in winter 2009-2010 which does not appear to be fully explained by changes in surface heat flux forcing, suggesting that the reduced heat transport across 26.5N may have played a role in this event. Significant findings include:

- The 2004-2010 mean AMOC strength from the RAPID-MOCHA array is 17.5 Sv. The first four years (2004-2007) showed stable annual means of 18.7 ± 0.5 Sv while 2009-2010 show lower values of ~15.0 Sv.
- Reductions in Ekman transport associated with the extreme low NAO phase over the North Atlantic in 2009-2010 contribute to the weaker AMOC, but changes in mid-ocean geostrophic transport also contribute significantly and actually precede the downturn in Ekman transports.
- The meridional heat transport shows a similar decline, from 1.33 ± 0.04 PW in 2004-2007 to approx. 1.1 PW in 2009-2010. Essentially all of this interannual variability is contained in the overturning heat transport component.
- Ocean heat content in the subtropical gyre north of the RAPID line shows a marked decrease in late 2009, coincident with the downturn in heat transport across 26.5°N. The heat transport divergence between 26.5°N and 41°N can approximately explain the magnitude and timing of this event.

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

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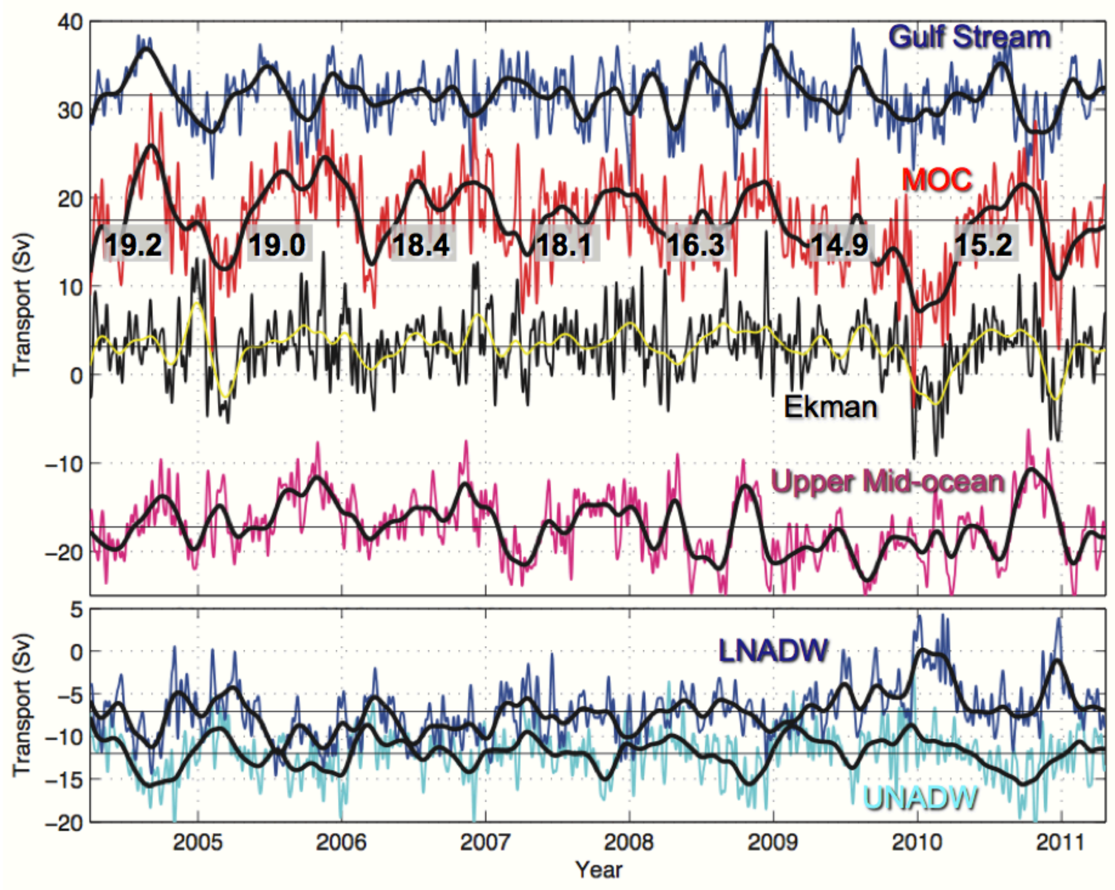

Figure 1. Top panel: Ten-day (colors) and three month low-pass (black or yellow) time series of the MOC transport (red) and its components: Gulf Stream (blue), Ekman transport (black), and upper mid-ocean transport (magenta), for the period 1 April 2004 to 22 April 2011. Annual mean values for the MOC during each year are shown in shaded boxes. Lower panel: southward transport of upper NADW, in the depth range 1100 to 3000 m (light blue), and lower NADW, in the depth range 3000 to 5000 m (dark blue).

Studies of the Influence of the Antarctic Circumpolar Current on the Atlantic Meridional Circulation

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The goal of this study is to develop conceptual understanding of the processes connecting the Atlantic meridional overturning circulation (AMOC) and the Antarctic Circumpolar Current (ACC). Our approach is to use a combination of numerical simulations and theoretical analysis to develop illustrative models of the key physical processes.

Most significant results (past two years)

1. A suite of numerical simulations demonstrated the importance of the ACC stratification in controlling the AMOC strength, and a secondary role of the direct influence of the Ekman transport and eddy-driven heat/salt exchanges at the ACC-Atlantic boundary. The interplay between the ACC stratification and surface density in the North Atlantic governs the AMOC response to a North Atlantic freshwater anomaly, and a delay in the ACC response to such forcing acts to amplify AMOC weakening (Kamenkovich and Radko 2011).

2. An analytical model of the Atlantic deep stratification and AMOC was developed in order to illustrate the dynamics of the ACC-Atlantic coupling. The results suggest the interpretation of the ACC as an active lateral boundary layer that does not passively adjust to the prescribed large-scale solution, but, instead, forcefully controls the interior pattern (Radko and Kamenkovich 2011).

3. The relationship between the air-sea density flux and isopycnal AMOC using IPCC AR4 model projections of the 21st century climate was explored, using the concept of the "push-pull" mode (Radko et al. 2008, JPO; also supported by this grant). The deep portion of this mode represents the combined effects of the adiabatic forcing in the North Atlantic and ACC. The push-pull mode and the actual isopycnal AMOC at the equator evolve similarly in the deep layers, both in the values of the linear trend and interdecadal variability. (M. Han MS Thesis 2011; Han et al. 2012 in press).

4. Surface signatures of recent climate changes in the ACC region and mechanisms that control these changes were examined using the analysis of data and simulations with idealized and comprehensive coupled models. The results suggest that the combination of the cooling effect of intensifying winds and the opposing effects of strengthening eddies must be accounted for when estimating the response of the ACC stratification, and related AMOC variability, to changes in climate (Kravtsov et al. 2011).

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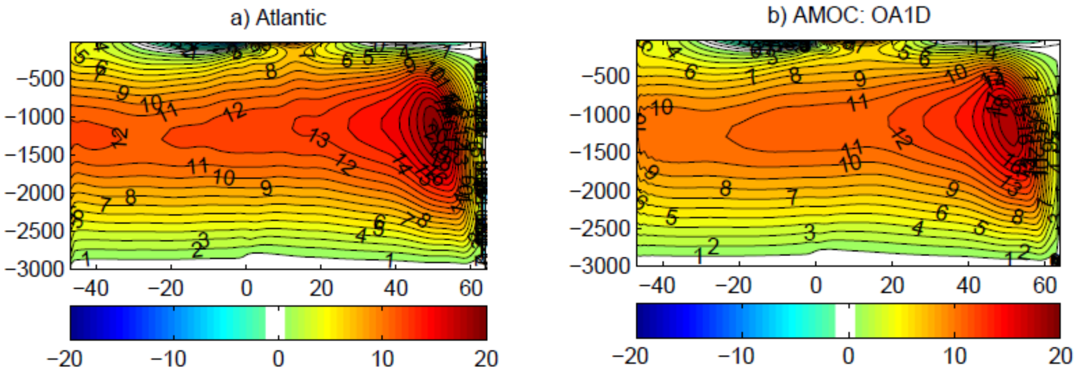

Figure 1: AMOC in two numerical simulations in: (a) an idealized global domain; (b) an idealized Atlantic-only domain with the prescribed, zonally-averaged ACC stratification at the southern boundary. Note that the AMOC strength (shown as an overturning streamfunction, in Sv) is very similar between these two cases, whereas in the Atlantic-only model without the prescribed ACC stratification, the AMOC strength is significantly weaker. This demonstrates the key role of the ACC stratification in determining the AMOC strength. These panels are the color versions of the figures in Kamenkovich and Radko (2011).

The Contributions of Ocean Circulation to North Atlantic SST

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The goal of this project is to determine the importance of various components of advection to interannual sea surface temperature anomalies in different regions of the North Atlantic Ocean, in particular, whether advection contributes to such large-scale SST patterns as the Atlantic Multidecadal Oscillation (AMO).

Recent Results

- Analysis of SST and heat flux fields showed the regions where and on what time scale ocean processes dominate in air-sea interaction. SST shows both the response of the ocean to atmospheric forcing and the forcing of the atmosphere by the ocean. On short time scales the tendency of SST is strongly positively correlated with the surface flux, indicating forcing of SST by the atmosphere. However, with increasing time scales, accomplished by lowpass filtering both flux and SST, the negative correlation between flux and SST becomes increasingly strong; this is the atmospheric response to changing ocean temperature. The time scale and the locations at which the magnitude of the negative correlation exceeds that of the positive correlation shows when and where ocean processes are the dominant contributor to SST anomalies (Fig. 1).
- A simple three-dimensional thermodynamic model is used to evaluate directly the contributions to SST in the North Atlantic Ocean (30-45oN, 40-75oW). The ocean is forced at the surface by QuikSCAT wind stress, OAFlux turbulent and ISCCP radiative heat fluxes. Geostrophic surface currents are derived from AVISO mean and anomalous sea surface height and are projected down into the water column using thermal wind from climatological density fields. The mixed layer model is combined with subsurface advection and diffusion to model the temperature of the water column. The contributions of surface heating, diffusion, mixed layer depth, entrainment, and geostrophic and Ekman advection are computed throughout the region for 2002-2009.

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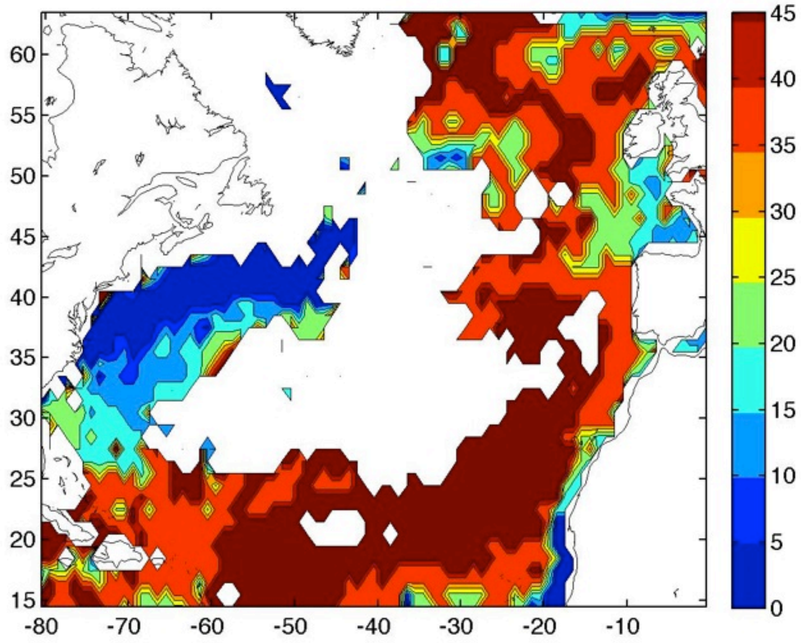

Figure 1. Time scale (in months) at which North Atlantic Ocean processes dominate in determining SST. The time scale at which the negative correlation between SST and surface heat flux (ocean dominance) has a larger magnitude than the positive correlation between the tendency of SST with surface heat flux (atmospheric dominance) is shown by the color contours.

Assessing Meridional Transports in the North Atlantic Ocean

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The goal of this study is to explain observed decadal anomalies of heat and freshwater in terms of the mechanisms that move water properties poleward. Aanalyses of high-resolution ocean models and altimetry and related observations focus on property transport anomalies and on the forcing mechanisms responsible for anomalies.

Recent Results

- An analysis of the contributions to North Atlantic sea level variability by graduate student Jinting Zhang showed that surface heating makes a substantial nonseasonal contribution and that the baroclinic Sverdrup balance accounts for much of the intergyre variability.

- An analysis of the Atlantic heat budget using thermosteric sea level and a simple Kalman filter reveals a high degree of meridional heat transport (MHT) coherence, from 30°S to 40°N. The analysis also shows increased (decreased) MHT correspond to increased (decreased) heat loss and increased (decreased) heat storage in the subtropical gyre.

- An analysis of the heat budget in the Gulf Stream and the North Atlantic Current using four different modeling systems shows that upper ocean heat transport convergence drives the heat budget in both regions with surface heat flux a much smaller contributor on interannual time scales, confirming earlier results by Kelly and Dong (2004). In addition, an analysis of a high resolution prognostic model shows that heat transport convergence variations result from changes in current structure and strength at the boundaries of the region rather than changes in temperature. A manuscript is in preparation on this topic to be submitted to J. Geophys. Res.

- Kelly and Dong (2004) also showed that the upper ocean heat content leads the flux of heat to the atmosphere by 3 months on interannual time scales. This relationship was confirmed in a high-resolution model in ECCO2 in collaboration with Dimitris Menemenlis. By examining each month of the year separately, we showed that the coupling between the ocean and atmosphere happens two times of the year, in late fall when the mixed layer nears its maximum depth, and in early summer, when the atmospheric boundary layer north of the Gulf stream is stable. Thompson and a French summer intern M. Garcia along with J. Booth (NASA GISS) , and K. Kelly have been exploring the relations in the Gulf Stream and the North Atlantic as a whole between heat stored in the ocean and surface heat flux. We find additional regions where the stored heat has more than 4 months lead to the surface flux from the atmosphere to the ocean. These regions include the Benguala Upwelling region, extensive regions of stable boundary layers North of the Gulf Stream in the summer, along the Eastern seaboard/the Florida Current during late summer. Minobe and co-workers identified these regions as places where the Gulf Stream influences cloud cover climatologically.

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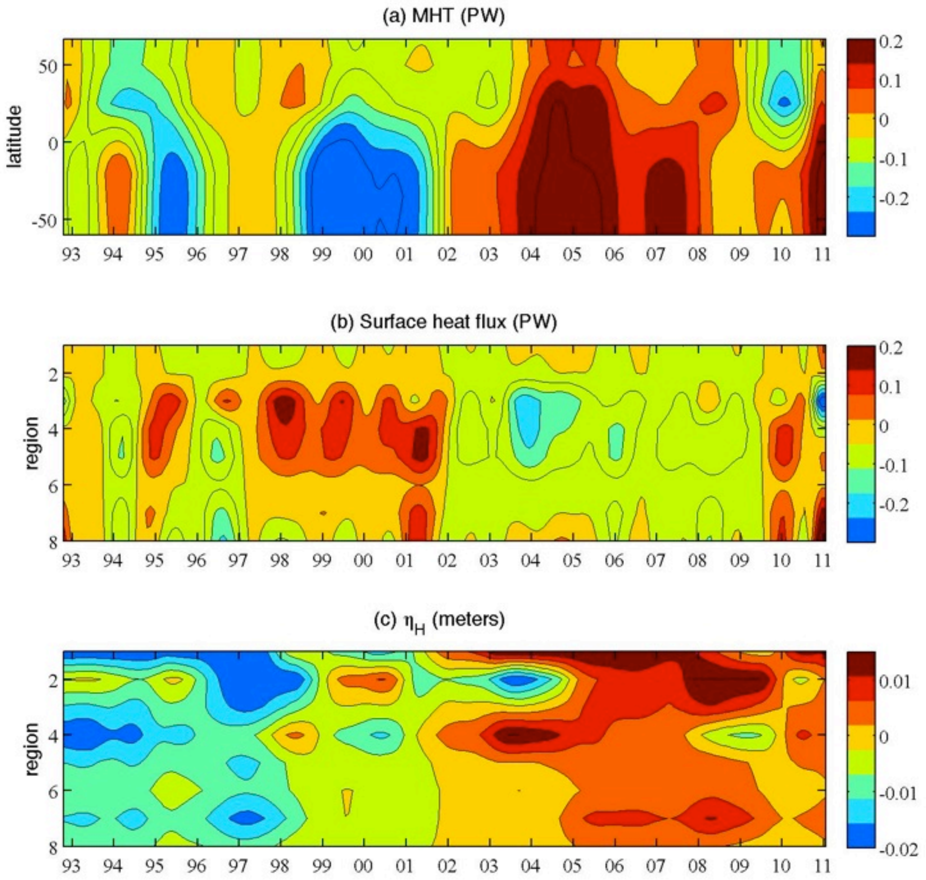

Figure 1. Meridional Heat Transport (MHT) and the heat budget. Time series reconstructed from (a) the first two EOFs of an estimate of MHT (PW), (b) the first two EOFs of surface heating (PW) and (c) the first two EOFs of thermosteric sea level (meters). Negative values in (b) correspond to ocean heat loss. Increases in MHT correspond to increased heat loss in the subtropical gyre, as well as increased heat storage.

Multiple Equilibria of Meridional Overturning Circulation

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A full characterization of the instability of the MOC would not be possible with the standard approach of multiple forward integrations using different freshwater forcing perturbations. We are thus developing Tangent Linear (TL) and Adjoint (AD) versions of POP ocean model to directly calculate freshwater forcings that create the largest change in the Atlantic meridional overturning circulation (AMOC).

Recent Results

Although many modeling studies are available in the literature showing the highly sensitive dependence of AMOC with regard to modeling parameters and variables, there exist still significant uncertainties in the model configurations such as mixing parameter values and initial and boundary conditions. Thus, the numerical experiments with the current POP TL and AD models were focused on analyzing how the fresh water forcing term interplays with the

AMOC calculation. A coarse resolution of 3 degree problem set with 60 vertical levels was used to integrate about one year of 10,000 time steps with the NCEP forcing conditions for 1985. In the test runs, it is found that the derivative computation of the highly nonlinear parameterization scheme of the vertical diffusion and viscosity computation routines requires a strong constraint for stable runs. This instability happens when the direct linearization scheme obtained through the automatic differentiation tool is applied without any constraint. In the current development of the POP TL and AD, a rather simple constraint scheme was applied to secure a more stable derivative computation. More detailed description of the current numerical experiments is:

- In the test runs of the POP TL and AD, a relatively small perturbation on the fresh water forcing was given and the POP TL was allowed to respond to the change throughout a whole year. Figure 1 b) shows small initial perturbation of the fresh water forcing fed to the TL model. It covers most of the Atlantic Ocean and some positive perturbation in the Northern Atlantic. According to the model structure of the POP model, any change from the fresh water forcing is first carried through the surface pressure calculation step in the barotropic module and then transferred to the barotropic and baroclinic velocity computation module. Figure 1 c) and d) show the responses of the longitudinal velocities computed in the barotropic and baroclinic modules with the TL. It shows that high impact is distributed over the Atlantic Ocean especially with the barotropic computation steps and the perturbation is carried to some portions in the Pacific Ocean as well. Figure 1 a) shows the TLM response of the stream function computed for AMOC in Sverdrups with regard to the forcing change. Matching the patterns of the given perturbation, more positive impact occurs within the Northern Atlantic Ocean.
- We could utilize the POP AD to see how all of the involved modeling variables interrelate to the given perturbation results. In this experiment, the perturbation was given only to the fresh water forcing term as input variable even with different scales at different locations. In theory, the AD model must be able to capture the initial perturbation patterns because the outputs of the TL model were exactly fed into to the backward adjoint integration. Figure 1 e) and f) show the gradient of the fresh water forcing variable computed through the backward adjoint integration at different time steps. As expected, the perturbation pattern of the initial fresh water forcing used in the TL model is recovered well from the adjoint calculations. It means that the dual set of the POP TL and AD models match well and the inverse modeling experiments with the POP TL and AD are for the first time practical.

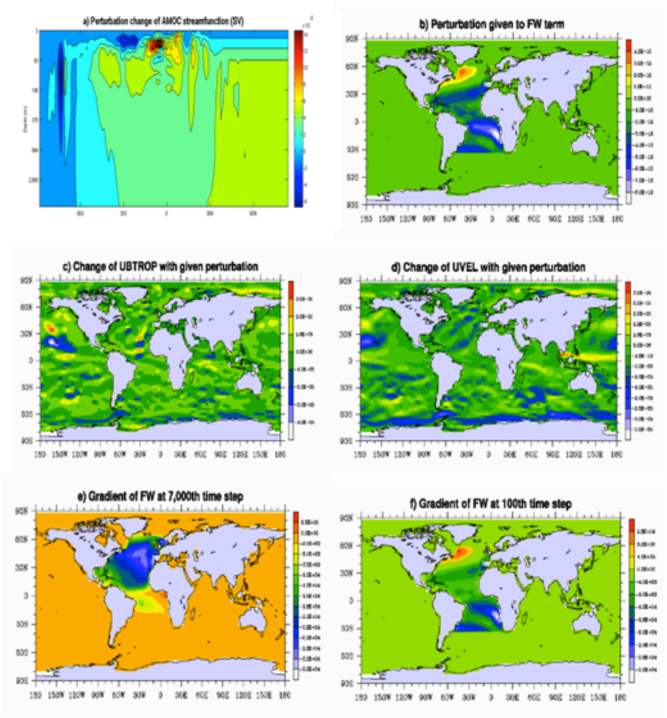

Figure 1. Forward and reverse propagation of the TLM and ADM derivatives of the modeling variables with the given perturbation to the fresh water forcing term: a) perturbation change of the AMOC stream function at 10,000 time step, b) initial fresh water forcing perturbation given to the POP TLM model run, c) and d) barotropic and baroclnic velocity perturbation computed with the TLM model at 10,000 time step, e) and f) gradient of the fresh water forcing term computed with the ADM model at two different time steps.

Atlantic Multidecadal Variability: Mechanisms, Impact, and Predictability: A Study using Observations and IPCC AR4 Model Simulations

PI: Yochanan Kushnir

Lamont-Doherty Earth Observatory

Research Goals: Systematically catalog the physical characteristics of Atlantic Multidecadal Variability in IPCC AR4 models, evaluate the associated climatic impacts over land, the link to AMOC and atmospheric variability, and assess its predictability.

Research Progress

- We are preparing a comprehensive manuscript summarizing our work on developing a new approach to LIM methodology to analyze GCM output. The study consists of applying a multivariate, first LIM fit to the GFDL CMWe have worked out theoretical details of using EOF space reduction in several steps to arrive at a LIM representation of the GFDL CM2.1 model ocean componet.
- The LIM representation of the GFDL CM2.1 ocean simulation is used to study the decadal prediction of the state of the North Atlantic by comparing between results from the perfect model runs with the full coupled GCM (Msadek et al., *Geophys. Res. Lett.* Vol. 37, 2010) with LIM prediction that are started from the same initial state. The goal is to assess whether there is information in the initial state that can be used to foretell if the forecast will be more or less skillful.
- We diagnosed and compare the characteristics global SST pattern related to the AMV and the phenomenon impact on the global distribution of surface air temperature and precipitation over land, in CMIP3/AR4 model simulations of the pre-industrial, 20th Century, and 21st Century climates and compared those to observations. We found that despite the differences in temporal characteristics of AMV variations (usually with shorter time scale compared to observed 60-80 years and less periodic compared to 20th Century observations) the spatial structure of the SST changes in the North Atlantic and globally and the precipitation impacts are not sensitive to the external forcing scenario, and are very similar to the observations (see figures in Ting et al., 2011 – reference below). These results support the assertion that the AMV is internal to the ocean-atmosphere system, and its spatial characteristics are insensitive to external radiative forcing.
- We began to analyze CMIP5 model output to examine the properties of the new-generation model simulations of Atlantic Multidecadal Variability.
- A manuscript is in preparation to describe the diagnostic analysis of the GFDL model simulations of North Atlantic low-frequency SST variability.

Highlights

- Diagnostic analysis of GFDL CM2.1 control output reveals a distinct quasi-oscilatory behavior that can be understood as resulting from stochastic atmospheric forcing of an internal ocean mode. The mode is potentially predictable becasue it decays rather slowly and it can also lead to explosive growth of SST anomalies with potential impact on the sourrounding climate.
- IPCC-class coupled model can simulate the pattern and global impact of AMV quite well, when compared to instrumeantal observations of the 20th century. Most models however, tend to display much shorter time scales for the related SST variations in the North Atlantic than assed from observations.
- AMV is insenstive to external radiative forcing in pattern, intensity, and global impacts on surface air temperature and precipitation over land.

Publications

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Decadal Variability of the Atlantic Meridional Overturning Circulation and Its Impact on the Climate: Two Regimes and Rapid Transition

PIs: Y.-O. Kwon[1], C. Frankignoul[1], [3], G. Danabasoglu[2]

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The objective of this project is to understand the mechanisms of the Atlantic meridional overturning circulation (AMOC) decadal variability and its rapid transition between the different regimes using multi-century integrations with the NCAR Community Climate System Model version 3 and 4 (CCSM3 and CCSM4) in present day or pre-industrial conditions.

Recent Results

(1) In addition to the previous analyses for the AMOC calculated based on the depth as the vertical coordinate (Kwon and Frankignoul 2012; Danabasoglu et al. 2012), the AMOC is constructed based on the density as the vertical coordinate for the CCSM3 and CCSM4 control integrations (Fig. 1). The meridional coherences of the AMOC decadal variability based on the two different coordinates exhibited a significant contrast in the subpolar latitudes (Fig.2). The density---based AMOC better represented the contribution from the subpolar gyre circulation and showed northward propagation of the AMOC anomalies carried by the gyre circulation. On the other hand, the depth---based AMOC emphasized the deep circulation and exhibited southward propagation of the AMOC in the subpolar latitudes. Combining information from the two representation provided a better understanding of the mechanism for the pronounced AMOC decadal variability in the CCSM3.

(2) Progress has also been made in understanding the transition from the first ~300 years with very regular and strong decadal (~20 yrs) AMOC variability to the following ~250 years of red noise-like AMOC regime with irregular and weak multi-decadal (~50 yrs) variability in the CCSM3. Increase of the density in the deep ocean below 2000 m appears to result in changes in the Labrador Sea convection and subpolar gyre circulation and consequently the AMOC variability.

(3) Atmospheric responses to the AMOC decadal variability in CCSM3 are examined based on the maximum covariance analysis (Frankignoul et al. 2012). A weak negative NAO-like atmospheric response is found in the strong oscillatory regime, while a more robust positive NAO-like response is detected in the red noise-like regime. The responses are

strongly dependent on the season. For example, the latter response is significant only in winter time and exhibits the same sign as the NAO prior to the AMOC, thus providing mechanism for a long persistency in AMOC in the red noise-like regime.

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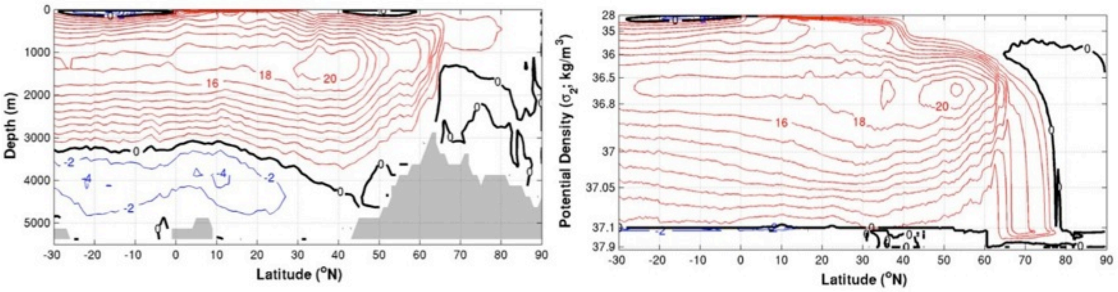

Figure 1. Mean AMOC streamfunction from the NCAR Community Climate System Modelversion 3 present-day control integration with the atmospheric resolution of T85 (CCSM3) for the model years 150-699, based on (left) depth (m) coordinate and (right) density (σ2) coordinate. Note that the density coordinate on the right panel is stretched for each density layer to be proportional to the total volume of that density layer in the whole Atlantic north of 30°S. Depth AMOC exhibits the maximum near 40°N associated with the crossover between the poleward surface current and the equatorward deep flow. On the other hand, the density AMOC has the maximum around 55°N reflecting the water mass transformation in the subpolar gyre.

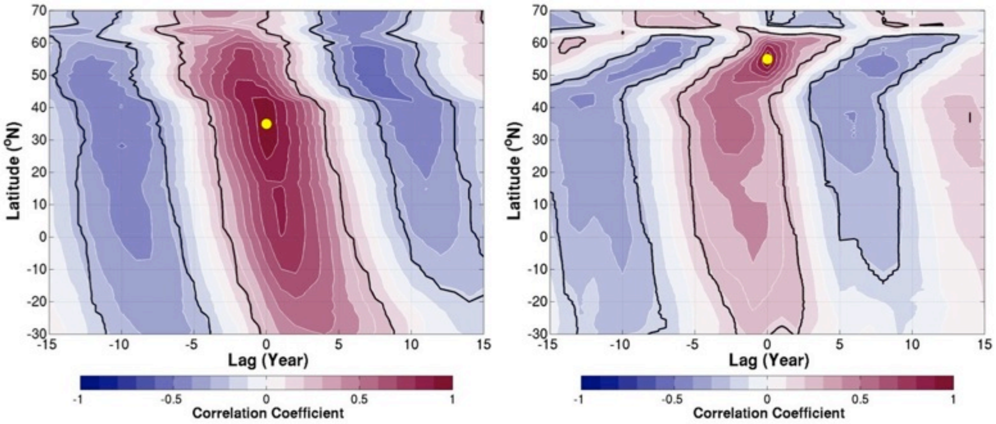

Figure 2. Meridional connectivity of the AMOC variability based on the annual mean CCSM3 AMOC for (left) depth (m) coordinate and (right) density (σ2) coordinate AMOCs. Color shadings are the lag-correlation between the maximum AMOC time series at each latitude and the one at a fixed reference latitude (indicated by the yellow dots). Note that the result is not sensitive to the choice of the reference latitude. The black contours indicate the statistical significance at 5% level. The meridional coherence implies potential predictability, while the two coordinate systems emphasize the contributions from different components of the AMOC, especially in the subpolar gyre.

Variability of the South Atlantic Meridional Overturning Circulation

PI: Felix Landerer
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The Meridional Overturning Circulation (MOC) is a key mechanism of meridional heat transport and thus highly relevant to regional and global climate. Much effort has gone into studying and monitoring variations of the Atlantic MOC in the North Atlantic Basin. This proposal will focus on the South Atlantic component of the MOC ('SAMOC'), for which currently no long-term in-situ observing system exists to monitor MOC strength and variability adequately. We propose to estimate the mass transport of the SAMOC using bottom pressure observations inferred from the GRACE satellite pair from 2003 onward, on 3-month averages, and to validate them using a combination of altimetry and Argo floats from 2006 onward. We will employ the latest GRACE observations in conjunction with an ocean general circulation model and ocean state estimation system to investigate in detail the processes affecting the geographic distribution of ocean bottom pressure variability arising from changes to the MOC on annual to inter-annual time scales.

We will first apply the GRACE-based method in the North Atlantic, where the AMOC is well monitored at specific latitudes to gain confidence in the error budget of our approach, and to select the most appropriate GRACE data processing strategies. In order to aid the interpretation of the observational estimates, we will test all methodologies on the ECCO2 ocean data assimilation product. By temporally and spatially filtering the model in a similar fashion as GRACE provides observations of surface mass density changes, we will assess the detection limits for this approach, and apply GRACE filter kernels that are most suitable for this application. We will then apply our techniques to the South Atlantic basin, where our preliminary analysis indicates the distribution of MOC-related bottom pressure variations is different from the North Atlantic. We will also assess the coherence between sea surface height and bottom pressure, and use information from regions with high coherence to extend the SAMOC time series to 1993. Finally, we propose to estimate the heat transport based on a relationship between volume transport and heat transport recently developed. The proposed research supports the AMOC program of U.S. CLIVAR by expanding the role and the utility of satellite observations.

The Arctic Observing Network at Critical Gateways—A Sustained Observing System at Davis Strait

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International Collaborators: Kumiko Azetsu-Scott[2], Brian Petrie[2], Charles Hannah[2] and Malene Simon[3]
[2] Bedford Institution of Oceanography, Dartmouth NS, Canada
[3] Greenland Institute of Natural Resources, Nuuk, Greenland

The Davis Strait project employs a system of long-term moorings, annual (autumn) hydrographic sections and autonomous gliders to quantify exchanges between the Arctic and Subarctic North Atlantic through the Canadian Arctic Archipelago (CAA). The measurement program began in September, 2004 and extends through October, 2015 under the current support. The project also includes extensive technology development aimed at addressing the severe observational challenges posed by the Arctic environment. The US National Science

Foundation Office of Polar Programs has supported the Davis Strait project under the Freshwater Initiative (OPP0230381), the International Polar Year (ARC0632231) and the US Arctic Observing Network (ARC1022472). The project has been carried out in collaboration with investigators from the Bedford Institution of Oceanography, with support from the Department of Fisheries and Oceans, Canada, and the Greenland Institute of Natural Resources. Data are available through the US Cooperative Arctic Data and Information Service (CADIS - http://www.aoncadis.org).

Recent results include

(1) Although there are no significant trends in 2004-2011 net volume and freshwater fluxes, efforts to identify trends in more narrowly defined quantities, such as the mean salinity of the Arctic outflow, have been more successful. For example, anomalously fresh Arctic waters observed in November 2009 flowing southward over the western Strait may be attributed to FW release from the Beaufort Gyre (Timmermans et al. 2011), with the FW signature also observed over the North Ellesmere Shelf (Jackson, personal communication) earlier in the year (January 2009).

(2) Azetsu-Scott (2012) use oxygen isotope composition to document the relative FW and FW flux contributions of sea ice meltwater, meteoric water and Arctic outflow. Nutrient concentrations were then used to further subdivide Arctic outflow into sea ice meltwater, meteoric water and Pacific water.

(3) The first year-round occupation of an Arctic region by autonomous gliders, achieved by linking two missions with a service interval in February in a narrow, ice-free region in the eastern Strait, just prior to the period when ship access became impossible. These missions provide a year-round time series of high-resolution sections across the Strait.

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Dynamics of the Descending Branch of the Atlantic Meridional Overturning Circulation

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The overall goal of our project is to identify the processes that cause upper-layer water to converge in the North Atlantic, thereby driving the large-scale, meridional overturning circulation (MOC).

Recent Results

Last year, one paper describing our research was published, and a second one was recently submitted. In our published paper, Schloesser et al. (2012), we obtained a quasi-analytic solution to a variable-density, 2-layer model (VLOM) forced only by a surface buoyancy flux. Key processes for driving the MOC involved the poleward thickening of the upper layer along the eastern boundary due to Kelvin-wave adjustments, the westward propagation of that coastal structure by Rossby waves, and their damping by mixing; the resulting zonal pressure gradient causes the surface MOC branch to converge into the northern basin near the eastern boundary.

In our submitted study, we extend the Schloesser et al. (2012) study to include forcing by a zonal wind stress $\tau^x(y)$. Much of the paper is devoted to the derivation and analysis of quasi-analytic solutions to VLOM; for validation, we also report corresponding numerical solutions to an ocean general circulation model (OGCM). Solutions are obtained in a flat-bottom, rectangular basin confined to the northern hemisphere. The buoyancy forcing relaxes upper-ocean density to a prescribed profile $\rho^*(y)$ that increases polewards until it becomes as large as the deep-ocean density at latitude y_2; north of y_2, then, the ocean is homogeneous (a 1-layer system), that is, it corresponds to the "convective" region of the model ocean. The wind stress τ^x drives Subtropical and Subpolar Gyres, and in our standard solution the latter extends north of y_2. Vertical diffusion is not included in VLOM (and is minimized in the OGCM); consequently, the MOC is not closed by diffusive upwelling in the interior ocean, but rather by flow through the southern boundary of the basin (into a southern-boundary sponge layer in the OGCM).

We find that solutions forced by τ^x and ρ^* differ markedly from those forced only by ρ^* (Schloesser et al. 2012) because water flows across y_2 throughout the interior of the Subpolar Gyre, not just near the eastern boundary. In some of our solutions, the strength of the MOC's descending branch is determined entirely by this mechanism, whereas in others it is also affected by Rossby-wave damping near the eastern boundary. Upwelling can occur in the interior of the Subpolar Gyre and in the western boundary layer, providing "shortcuts" for the overturning circulation; consequently, there are different rates for the convergence of upper-layer water near y_2, M_n, and the export of deep water south of the Subpolar Gyre, M, the latter being a better measure of large-scale MOC strength.

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Decadal and Multidecadal Variability of the AMOC in Observational Records and Numerical Models

PIs: M. McPhaden[1], D. Zhang[1,2], W. Cheng[1,2]
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The purpose of this project is to identify and investigate variables and processes that have been relatively better observed and can be associated with decadal-to-multidecadal changes of AMOC, and to examine these processes in climate model simulations.

Recent Results

A multidecadal transport timeseries of the North Brazil Current (NBC) is derived from historical hydrographic data. It is demonstrated that this transport variability is dynamically linked to the Labrador Sea deep convection in both observation and the GFDL coupled climate model CM2.1 (Zhang et al. 2011). Further, the NBC transport is found to highly correlated with the AMOC transport in all climate models that we have diagnosed (including 10 CMIP5 models), suggesting that the NBC is a robust indicator of the decadal-multidecadal variability of the AMOC. Another significant result of this project is that decadal upper ocean salinity anomalies in the western tropical and subtropical Atlantic thermocline is correlated with the NBC (and AMOC) transport, and these anomalies lead salinity anomalies in the eastern subpolar gyre by 5-8 years, suggesting that much of the recently observed salinification in the eastern subpolar gyre is a result of the AMOC variation. This result is robust in both historical observations and NCAR forced ocean model hindcast. Analysis of the model results indicates that the lower latitude salinity anomalies are linked to the interaction of the AMOC and the shallow wind-driven subtropical cell of the North Atlantic. The results were presented at the AGU Ocean Science Meeting 2012 and a manuscript by Zhang and McPhaden et al. is in preparation.

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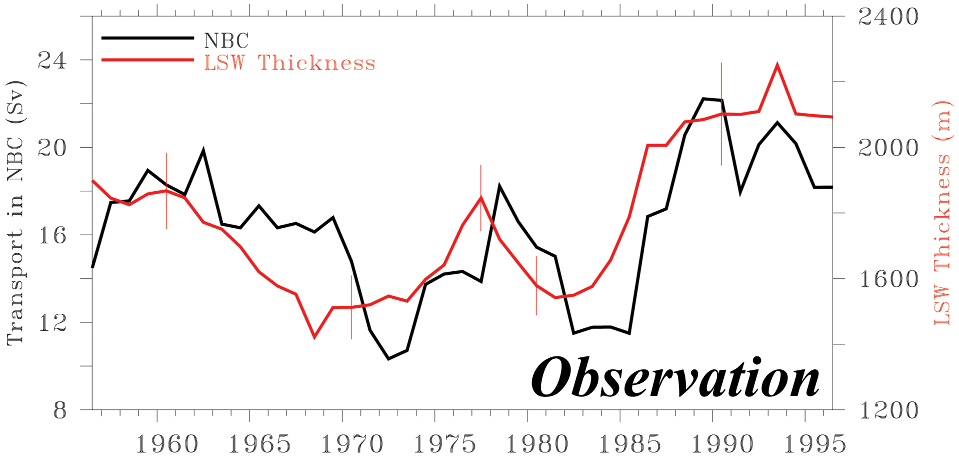

Figure 1. The NBC geostrophic transport at 6°S (black), calculated from historical hydrographic data, and the observed Labrador Sea Water (LSW) thickness representing the variability of the Labrador Sea deep convection (red). The LSW variability leads the NBC transport by about 3 years. This relatively short time scale of lower latitude AMOC adjusting to subpolar forcing is consistent with previous high-resolution eddy permitting model studies.

Southwest Atlantic MOC project ("SAM")

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This project is designed to measure both the warm-upper and cold-deeper flows associated with the Meridional Overturning Circulation (MOC) near the western boundary at 34.5°S in the Atlantic. The project also augments an existing long-term program that estimates meridional volume and temperature transports using quarterly trans-basin expendable bathythermograph sections along 35°S. 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. As of October 2012 the SAM array has collected about 3.5 years of data near the western boundary, and the bulk of the array will be recovered, equipped with fresh batteries, and redeployed in December 2012. The Brazilian partners will be deploying their moored components in December 2012, while the French and South African partners will be deploying their moored instrumentation in mid-2013.

The SAM program is still in its early stages, with the first publication based on the SAM data being now under review. The data demonstrate that the Deep Western Boundary Current

(DWBC) is highly variable at 34.5°S, with variations of 40+ Sv occurring over a few days and transport anomalies of 20+ Sv persisting for months. Other key results include:

- Baroclinic transport fluctuations estimated relative to an assumed level of no motion are statistically uncorrelated to the actual absolute DWBC transports, with the transports associated with the non-zero reference layer velocities at times greatly exceeding the baroclinic variations.
- Variability of the DWBC transport at 34.5°S is of comparable magnitude with the DWBC variations observed at 26.5°N, which is somewhat surprising given the fact that only part of the deep limb of the MOC is believed to be on the western boundary at 34.5°S (with the rest believed to be flowing southward along the western continental slope of Africa).
- Comparison to 27-years of output from a high-resolution global model, the Ocean general circulation model For the Earth Simulator (OFES), demonstrates that at least ~5 years of data are needed before an array in the SAM location would capture the full range of variance exhibited in the longer model run. Because the variability in the model is significantly smaller than the observed variability over time periods comparable to the existing moored observations, it is likely that the 5 year estimate is a lower bound.

More information is available online:

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

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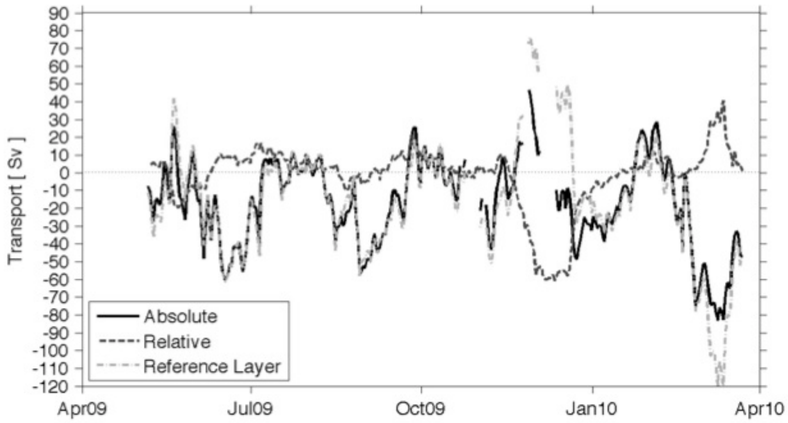

Figure 1. Transport of the Deep Western Boundary Current at 34.5°S, integrated between 51.5°W and 44.5°W and between 800 and 4800 dbar (or the bottom, where it is shallower). The total absolute transport is shown (solid black line), as is the transport determined relative to an assumed level of no motion at 800 dbar (dark gray dashed line) and the transport associated with the non-zero velocity at the reference layer of 800 dbar (light gray dash-dot line). Figure modified from Meinen et al., 2012.

A NOPP Partnership for Atlantic Meridional Overturning Circulation (AMOC): Focused Analysis of Satellite Data Sets

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A targeted exploratory analysis of long time series of satellite data sets over the Atlantic Ocean was conducted to attempt to lay the foundation for the identification of signatures of changes in the Atlantic Meridional Overturning Circulation (AMOC). The satellite data sets were multi-decadal time series of sea surface temperature from infrared radiometers and surface wind speeds. This project has now come to an end.

Recent Results

Further study conducted in this project involved assessing linkages between the SST fields of the entire North Atlantic Ocean and the strength of the AMOC as revealed in the current meter moorings at 26.5ºN of the Rapid-MOCHA (Rapid Climate Change–Meridional Over-turning Circulation and Heatflux Array) Project (Cunningham et al. 2007; Rayner et al. 2011). The current-meter array has been providing data since April 2004.

Our analysis began with the AMSR-E SST time series, but even though this covers much of the period of the Rapid–MOCHA measurements, it was too short for significant relationships to be derived for some of the statistical analyses. We then moved to the "Reynolds" Optimally Interpolated SST fields that are based on measurements of AVHRR (Reynolds and Smith 1994). This is now a 30-year time series on a 1° × 1° latitude-longitude grid. Additional meteorological data were taken from the NCEP-NCAR reanalysis data at a 2.5° × 2.5° spatial resolution (Kalnay et al. 1996); in particular the sea-level pressure fields were used. The domain for this investigation includes both Extratropical North Atlantic (ENA, 20°-70°N, 90°W-0°) and Subpolar North Atlantic (SPNA, 45°-70°N, 90°W-0°).

Monthly anomalies over the period were constructed by subtracting the mean seasonal cycle from the monthly data. Then, at each grid point, a linear trend was removed from the anomaly time series, eliminating trends not associated with AMOC variability in the analysis period. In addition, fields are weighted by the square root of the cosine or latitude to balance the spatial contribution of all the grid points in the eigenvector analysis. To give similar weight to each month in the analysis period, the monthly anomalies were then normalized by a mean seasonal cycle of standard deviation. Similar operations are applied on the 12-hourly, 10-day low pass filtered transport time series starting from April 1st 2004 to April 22nd 2011 (85 months) for AMOC and layer transports at 26.5°N are obtained from Rapid-MOCHA Program. Singular Value Decomposition (SVD) analysis is a powerful technique to reveal the links between two fields by providing spatial patterns and time expansion coefficients (time series).

Our hypothesis to remove the atmospheric contribution to the SST variability is simply:

$$\mathrm{SSTA}(t) \approx \alpha \mathrm{NAO}(t \pm \Delta t) + \mathrm{RESSTA}(t),$$

(1) which states that SST variability results from a linear combination of contributions coming from the preceding or lagged atmosphere, which is represented by the NAO, and a residual part (RESSTA), which could reflect the impact coming from the ocean. To calculate RESSTA, the SST anomaly is represented by the SVD first mode time series SSTA (S1) and NAO is represented by the SLP SVD first mode time series SLPA (S1) rather than NAO index for the reason that, the simple two point pressure difference index of NAO might limit dynamical changes in spatial patterns, such as an eastward shift of the center of NAO variability (Hilmer and Jung, 2000).

Time series of the RESSTA and the available AMOC layer transports at 26.5°N are compared in Figure 1. Both RESSTA calculated in SPNA and SSTA(S1) are highly correlated with the observed AMOC Upper Middle Ocean (UMO) transport anomaly at 26.5°N, leading the latter by 1 to 4 months (r<UMO, SSTA (S1)>=0.85; r<UMO, RESSTA>=0.87, 6 month boxcar filtered, 99% significant, also 99% significant when unfiltered).

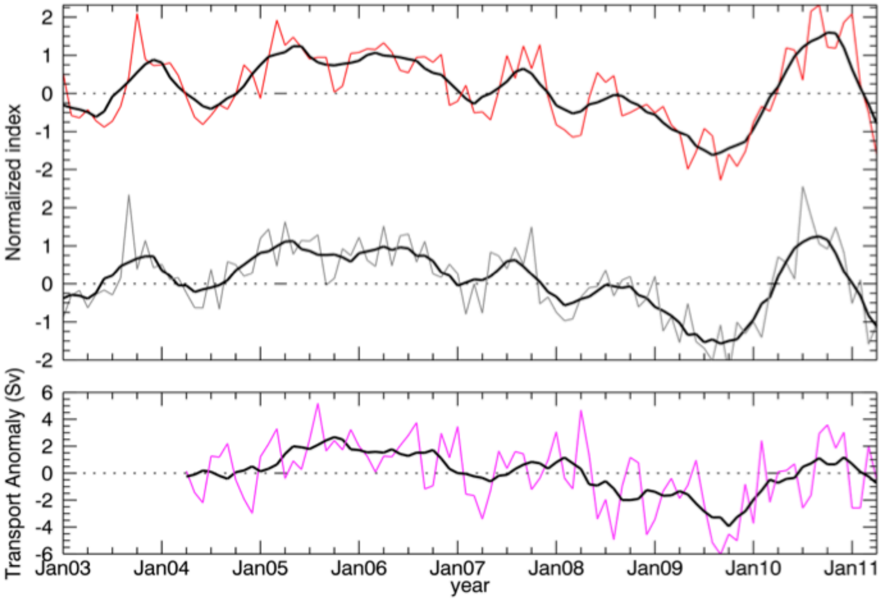

Figure 1. *Time series of SSTA(S1) (red) and RESSTA (grey) and UMO (magenta).*

To better clarify the link between the NAO and with AMOC, and to differentiate the contributions from each component of the AMOC transport (Gulf Stream, Upper Middle Ocean and Ekman), regression maps of SSTA on different normalized indices are generated. Maximum positive anomaly regressed by SSTA (S1) is about 0.7K is more than twice of that regressed by SLPA(S1) or NAO. The resemblance between regressions of SSTA (or RESSTA) and AMOC upper middle ocean (UMO) transport components suggests the residual large part of SPNA SST variance is able to indicate ocean interior variability and as shown in Figure 1, such warming patterns of SPNA SST is followed by a strengthening of AMOC (or weakening UMO) at 26.5°N. These results were confirmed by an analysis of simulations of the GFDL CM2.1, 500 year control run. A publication is in preparation.

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

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Analysis of 18,864 hydrographic profiles from our 3-year NSF-sponsored field program with Seagliders at the Iceland-Faroe Ridge forms the core of this project. N.L.Beaird, graduate student under this grant, is carrying out much of the work, in collaboration with PIs Rhines and Eriksen. Dr. Ilker Fer of Univ of Bergen has collaborated on a study of turbulent mixing which roughly doubles the transport of the dense overflow. In addition to hydrography the data returned includes vertically averaged horizontal velocity, surface velocity, fine-scale vertical velocity, oxygen and bio-optics. Sections between Iceland and Faroes, transverse sections crossing the Ridge, and within the Faroe-Bank Channel provide many portraits of the dense overflows entering the Atlantic (and accounting for roughly ⅓ of the total dense overflow transport).

Recent Results
The two pathways for dense overflows east of Iceland are captured by this dataset. In the intense, concentrated Faroe Bank Channel, the site of roughly 2.5 Sverdrups of dense water transport, intense mixing transforms the overflow into a warmer, lighter water mass. The Seaglider's known flight characteristics allow measurement of fine-scale vertical velocity, which in turn provides an estimate of active turbulent mixing that yields this watermass transformation. The method has been developed by E. Frajka-Williams for Labrador Sea glider data, and, by N.L.Beaird using comparisons with nearby *in situ* velocity microstructure profiles from the free-fall instrument of Dr. Ilker Fer. While vertical velocity variance is shared between internal waves and turbulent overturns, spectral filtering is able to extract estimates of mixing in these overturns. The advantage is in having many thousands of profiles to build up statistics of this important process. This work has now been published (Beaird et al. 2012a).

The second overflow pathway is southward across the 500 km long Iceland Faroe Ridge. This is the site of the extensive polar front, with warm Atlantic Water flowing northward above the front, which is sharp and is draped over the south flank of the Ridge. Beneath it, a thin layer of dense water moves along the ridge and downward, in episodic bursts. The Seaglider measures depth-averaged horizontal velocity and geostrophic cross-path velocity profiles; these have been digested into a model of the occurrence of strong dense-water events. The two pathways join to produce the Northeast Atlantic Deep Water (NEADW, a.k.a. Iceland-Scotland Overflow Water, ISOW) which supplies roughly 1/3 of the North Atlantic Deep Water (NADW), the major artery of the global overturning circulation. Unlike some numerical simulations of the overflow, the dense water does not seem to break into isolated boluses as the two pathways join. The migration downslope from ~800m to roughly 2500m, while out of the range of this dataset, occurs as the dense water precedes round the Iceland Basin. The paper describing the Iceland-Faroe Ridge part of the dataset is available in preprint form (Beaird et al. 2012b).

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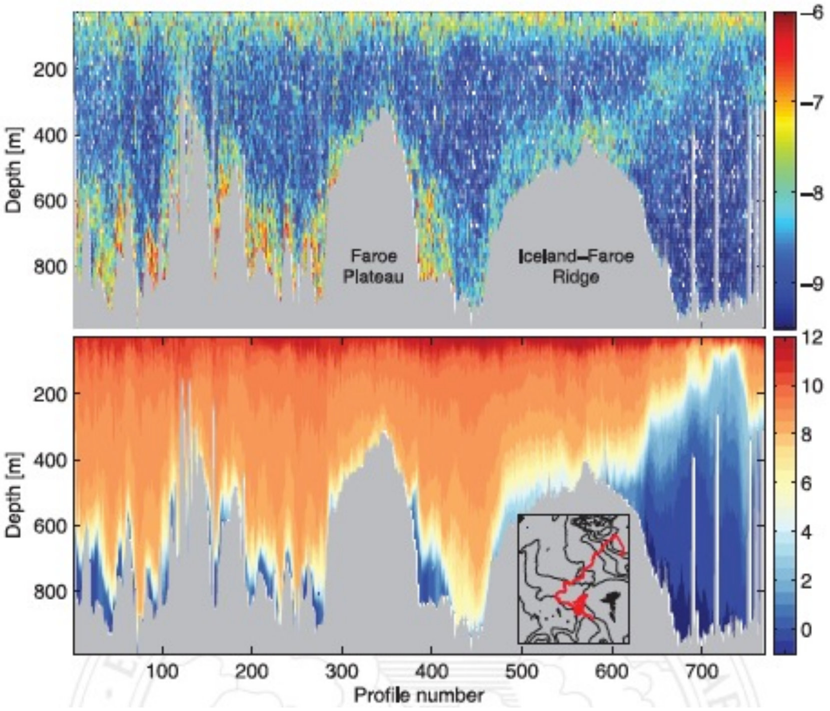

Fig. 1. (top) Multiple crossings of the Faroe-Bank Channel overflow, and then the Iceland Faroe Ridge, from more than 700 profiles in a single Seaglider deployment. Depth vs profile number section of dissipation, log10(dissipation), W kg^{-1} ; (bottom) corresponding temperature section (8C). Map inset shows the path of the glider.

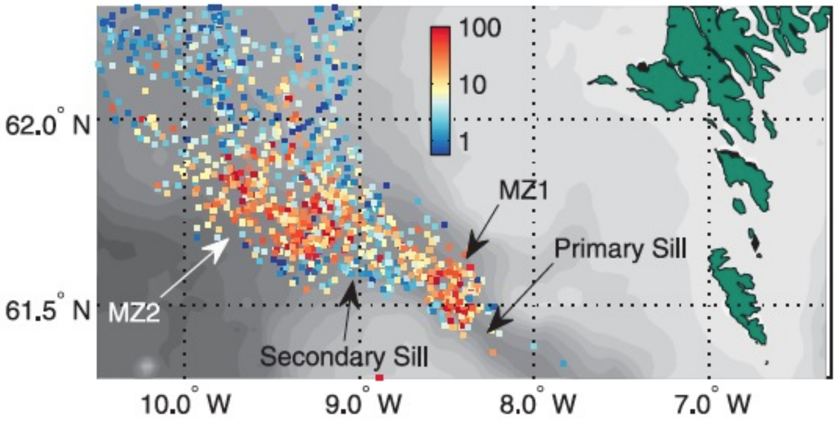

Fig. 2. Vertically integrated dissipation rates in the Faroe-Bank Channel outflow, the site of the dominant mixing with sets the properties of NEADW in the North Atlantic Deep Water.

Pathways of Meridional Circulation in the Climate System

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The warm branch of AMOC involves the Gulf Stream and complex pathways from subtropics to the subpolar gyre and Nordic Seas. Establishing spatial patterns of this circulation and of related ocean water-column heat content are the goals of this NASA OSTST project. We have updated the decadal variability of the Atlantic subpolar gyre circulation seen through satellite altimetry and SODA assimilated hydrographic fields, and established the connection between the recent major warming of the northern Atlantic and multi-decadal 20th Century ocean climate variability.

Linkages between altimetric sea surface height (SSH), subpolar gyre intensity, atmospheric forcing have been extended to interannual and multidecadal variability ocean heat content. The time series of the first EOF of the altimetric SSH is still on a nearly monotonic downtrend from the values of the early 1990s, the subpolar gyre weakening by about 20 cm of altimetric SSH. Its corresponding vector surface current field shows strong deceleration of western and northern boundary currents. EOF analysis of the observed 700-meter ocean heat content shows a close relation to the time series of the first SSH EOF mode. The decline of subpolar surface circulation accompanies massive warming of the subpolar Atlantic and Nordic Seas, while the secular increase in heat content resides primarily in subtropical gyres. Advection is driven by a windstress-curl EOF mode and corresponding air-sea heat flux anomalies that mimic the shape of the subtropical and subpolar ocean gyres, bringing more subtropical waters into the subpolar gyre.

The altimetric SSH shows the transition of the Atlantic Multidecadal Variability (AMV or AMO) from cold phase to warm phase. These cycles involve changes in the warm branch of the Meridional Overturning Circulation (AMOC). The subpolar time series shows also an abrupt change in 2010, correlated with a sudden drop of several Sverdrups in the AMOC at 26.5N, recorded by the RAPID array. Oceanic water-column heat content (OHC) is the key variable expressing roughly 90% of the storage of anthropogenic global warming. Its spatial structure and variability is correlated with the SSH patterns we discuss here.

Modes of interaction with the atmosphere are described: over the entire 20th Century, warm northern Atlantic associated with recurring blocking patterns in the Atlantic storm track. It is remarkable that high-frequency 'weather' is modulated at decade-to-century timescale in this way. The interconnectedness of AMOC across a range of latitudes, long in question, is seen in the recent sudden lurch of the system in 2010.

- At 10 – 50 year timescale, warm Atlantic ocean corresponds to increased blocking episodes, weak subpolar gyre circulation and, cold central Europe winters.
- The two principal EOFs of wind-stress-curl correlate with winter blocking frequency, separately Greenland and European blocking.
- The warm, northward flowing branch of AMOC meridional circulation has been active in creating the most recent AMO/AMV warm period in the subpolar Atlantic.
- Extreme atmospheric blocking events occurred in the late 2000s, corresponding to sudden lurches of AMOC at 26.5N.

H. Langehaug of Univ of Bergen successfully completed her Ph.D. dissertation which has investigated watermass transformation in the subpolar mode water (SPMW) of the Atlantic, as represented in three coupled climate models. The warm and saline Subtropical Water carried by the North Atlantic Current undergoes substantial transformation on its way to higher latitudes, predominantly from oceanic heat loss to the atmosphere. The geographical distribution of the surface forced water mass transformation is assessed in multi-century climate simulations from three different climate models (BCM, IPSLCM4, and MPI-M ESM), with a particular focus on the eastern subpolar North Atlantic Ocean. A diagnosis, originally introduced by Walin (1982), estimates the surface water mass transformation from buoyancy forcing. While the depth structure of the Atlantic Meridional Overturning Circulation (AMOC) is similar in all models, their climatological heat and freshwater fluxes are very different. Consistently, the models differ in their mean pathways of the North Atlantic Current, location of upper ocean low salinity waters, as well as in sea ice cover. In the two models with an excessive sea ice extent in the Labrador Sea, most of the water mass transformation in the subpolar region occurs in the eastern part (east of 35°W). The eastern water mass transformation has pronounced variability on decadal timescales in all models. An increase in this transformation is found to follow an increase in the strength of the overturning in density space (in two of the models), which is associated with an increase in the warm northward flow. In the third model, this link between the transformation and northward flow is not found, perhaps due to a weak circulation and subduction of the North Atlantic Current at the entrance of the subpolar region.

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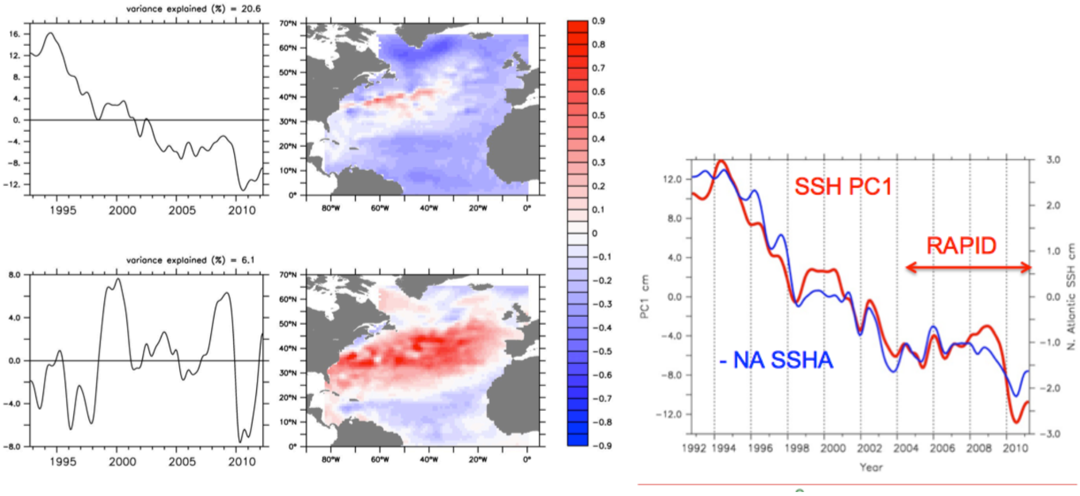

Fig. 1. (top) EOF 1 and EOF 2 of the North Atlantic altimetric sea-surface height (SSH) based on observations from **1992 to 201**1; (bottom) principal component time series, PC1 (red) and simple average of -SSH over the N Atlantic (blue). The period of the RAPID measurement array at 26.5N is shown. Note the large footprint of the sudden 2010 event.

Transport Pathways in the North Atlantic: Searching for Throughput

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This project seeks to clarify the transport pathways of the North Atlantic meridional overturning circulation (MOC). The work is motivated in part by discrepancies between Eulerian transport estimates and the behavior of floats and drifters in the upper and lower limbs of the MOC. Various methods including trajectory statistics and dynamical systems analysis are used to map the Lagrangian structure of the flow and to describe and quantify the intergyre water mass exchanges. Particular attention is paid to the role of the Gulf Stream Current in preventing the subtropical-to-subpolar gyre transport.

An important biological application is considered, which aims to understand transport of American eel larvae from the spawning location in the Sargasso Sea to coastal waters of the Gulf of Maine, where larvae mature and make their way into fresh waters. Our analysis suggest that without active swimming, only a small number of larvae are able to cross the Gulf Stream Current and reach the entrance to the Gulf of Maine. The role of larva's diurnal vertical migration and active swimming ability is now being investigated.

Studying the Modulation of Extremes in the Atlantic Region by Modes of Climate Variability using a Coupled Regional Climate Model

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Extreme weather and climate events, such as hurricanes, heat waves, and intense rainfall, usually occur on local and regional scales. However, the frequency and intensity of their occurrence are modulated by planetary scale modes of climate variability, such as the El Niño-Southern Oscillation and the Atlantic Multidecadal Oscillation. The modes of climate variability involve interactions among different components of the climate system, including the atmosphere, ocean, land, and sea-ice. The current generation of global Coupled General Circulation Models (CGCMs), with coarse horizontal resolution of the order of 100 km, is not capable of fully resolving the small-scale processes that play a vital role in the occurrence of extreme events. The goal of our research is to use a coupled regional climate model (CRCM) to assess the effect of fine spatial resolution and air-sea coupling on extreme events in the Atlantic region. The CRCM is comprised of a regional atmospheric model coupled to a regional ocean model, with lateral boundary conditions derived from either observations or global CGCM simulations.

Recent Results

Unlike global atmospheric models, which are usually configured with an optimal combination of “tuned” parameterization settings for good climate simulations, regional models, like the WRF model used in the CRCM, must typically be tuned to produce the best simulations in the region of interest. We explored the parameter space of the WRF model, by using different choices for convection, radiation, and boundary layer parameterizations, with the goal of producing the best possible simulations over the U.S. region as well as the tropical Atlantic regions, to better study the extremes. During this tuning exercise, we were able to identify two combinations of model parameters that gave rise to a “wet” and “dry” Amazon simulation. We carried out both coupled and uncoupled RCM sensitivity integrations using the "wet" and "dry" parameters, and determined that surface wind biases in the eastern equatorial Atlantic, *not* in the western equatorial Atlantic, were likely a major cause of biases in the coupled simulation often seen in CGCMs (Patricola et al. 2012).

We have also carried out simulations of hurricane activity using the CRCM. When observed sea surface temperature is used as the boundary condition, the atmospheric component of CRCM can reproduce the observed variability in hurricane activity quite well (Figure 1). Being a coupled model, the CRCM can also simulate *barrier layers*, which are oceanic regions where the depth of the isothermal layer exceeds the depth of the mixed layer. They are known to occur in certain regions of the tropical Atlantic, especially the Caribbean. The presence of a barrier layer inhibits vertical mixing and can reduce the negative oceanic feedback on hurricane development. We have carried out an analysis of hurricane-barrier layer interaction in observational data and compared it to the simulated interaction in the CRCM. Our results show that the intensification rate for hurricanes can be significantly amplified by the presence of a barrier layer (Balaguru et al. 2012).

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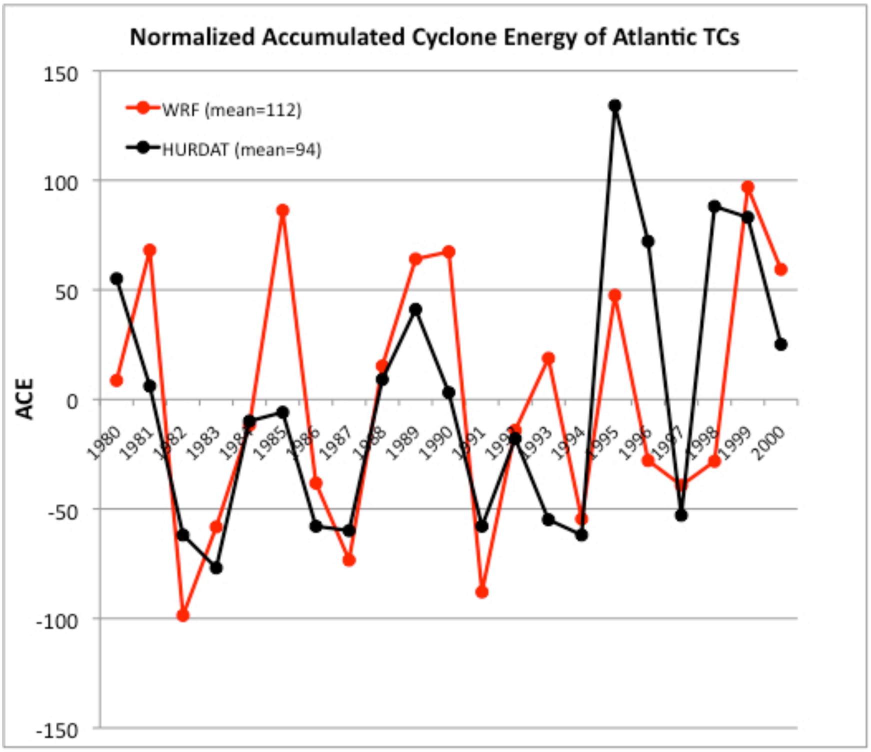

Figure 1. Time series of normalized Accumulated Cyclone Energy (ACE) of Atlantic Tropical Cyclones from 1980-2000 in observations (black) and 20-year AMIP-style simulations using WRF with observed sea surface temperature boundary conditions (red). Note the positive correlation between observed and simulated ACE.

Satellite Monitoring of the Present-Day Evolution of the Atlantic Meridional Overturning Circulation, Investigation Period: March 1, 2009 – February 28, 2013

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The objectives of this project include the use of contemporary satellite measurements (radar altimetry sea-level and current velocities, GRACE ocean bottom pressure and Greenland melt-water freshening fluxes, sea surface temperature), and tide gauge sea-level and hydrographic data (sea-level and subsurface current velocities) to establish an observational system potentially capable of monitoring the present-day evolution of the Atlantic Meridional Ocean Circulation (AMOC). Our project intends to address the following scientific questions: (1) what is the current state of the AMOC? (2) How has the AMOC varied in the past on the interannual to decadal or longer time scales? (3) Is the AMOC evolution correlated with basin-scale sea-level change?

Recent results

(1) We have developed the methodology and computed surface and subsurface current velocity time series using radar altimeter data (ERS-2 and Envisat) and Argo in the North Atlantic Ocean, with the surface current velocity evolution spanning longer than a decadal time span, 2000–2012, and the subsurface current velocity has a time span of 2003–2012.
(2) The closure of the present-day (2002–2012) sea-level budget is limited by the accuracy of the sea-floor uplift modeling due to the glacial isostatic adjustment process, and by the short data span of the modern sea-level measurements (Argo, altimetry, GRACE).
(3) The hypothesis that low-frequency geocenter motion could be induced by uneven present-day melting of glaciers and ice-sheets, its contribution to accurate sea-level measurements using satellite altimetry, and its possible detection, is beginning to indicate that it may be rectifiable with our theoretical treatment and data analysis.

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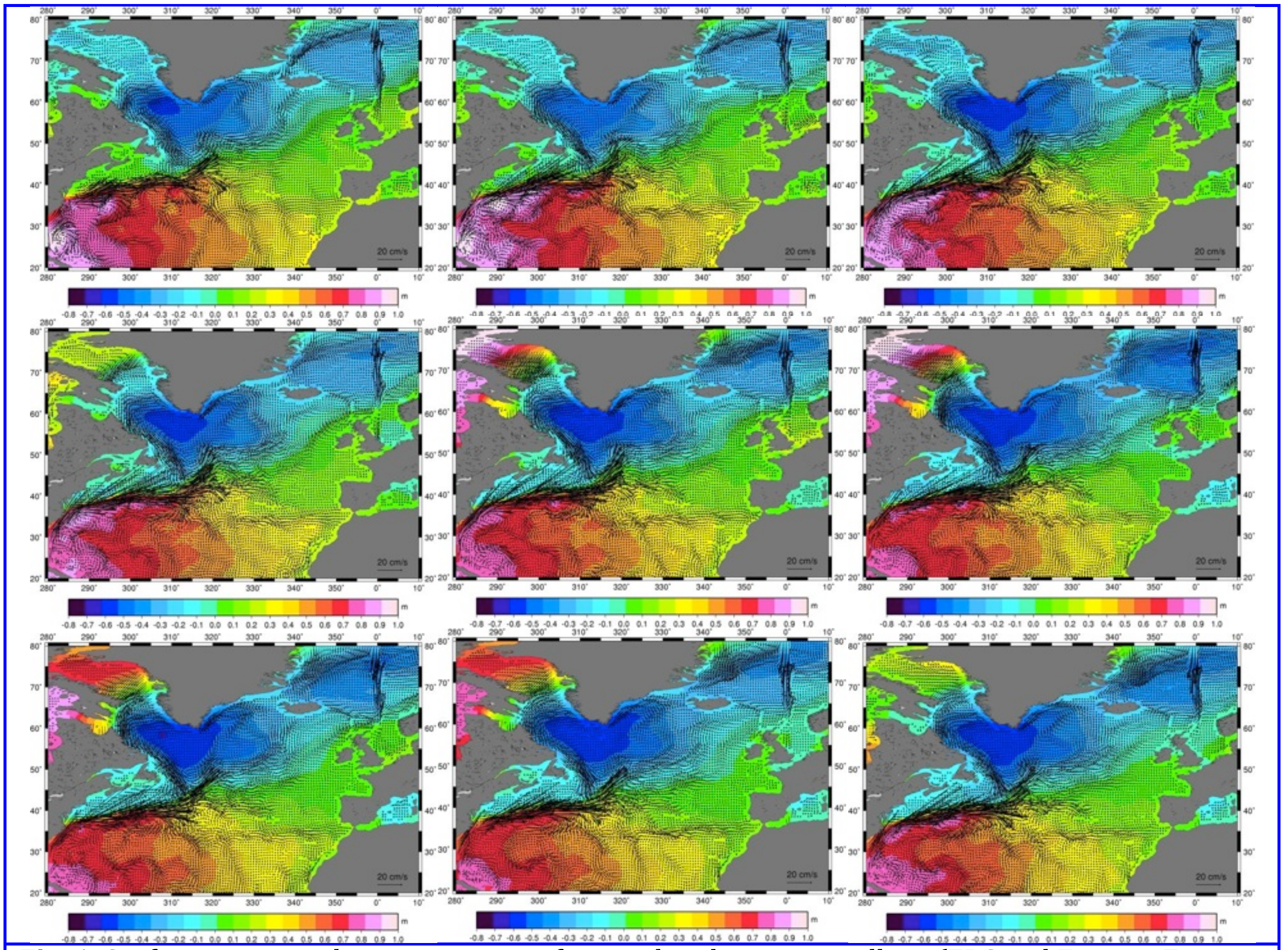

Fig. 1. Surface current velocity time series from radar altimeter satellites (ERS and Envisat, Envisat results are shown here) relative to GOCE or EGM08 modeled geoid or equipotential surface. **Top**: September, October, November 2002. **Middle**: December 2002, January, and February 2003. **Bottom**: March, April and May 2003.

From Rivers to the Ocean: The Dynamics of Freshwater Export from Hudson Strait

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International Collaborators: Y. Gratton[1], S. Dery[2]
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This project seeks to quantify the variability of the freshwater export from Hudson Strait, the third largest oceanic contributor of freshwater to the North Atlantic, and to understand which processes regulate its variability. It involves the analysis of moored data, a high resolution regional process model and an idealized model. A series of papers showing that the freshwater export is strongly dominated by the regional wind forcing, on interannual time scales, and to the river input variability on longer time scales have been published this year. A synopsis of the observed freshwater outflow was presented at the IPY meeting in 2012, and is presently being written up for publication.

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Glacier-Ocean Coupling in a Large East Greenland Fjord

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The objective of this project is to investigate ice-sheet ocean interactions in one major glacial fjord, in southeast Greenland, and determine what oceanic processes control the rate of submarine melting and, hence, influence the stability of the outlet glacier. Results obtained and published within this project have shown that oceanic variability (including changes in the upper limb of the AMOC) are rapidly transmitted to Greenland's glaciers and have the potential to affect glacier stability. A paleo reconstruction from a major glacial fjord shows that glacier retreat is strongly tied to oceanic variability. Finally, a review of existing data from other fjords, shows that waters of Atlantic origin reach and drive melting of glaciers all around Greenland.

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Mode Water Formation in the Lofoten Basin – a key element of the MOC

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The goal of this project is to investigate the transformation of Atlantic Water in the Lofoten Basin – which dominates much of the warm to cold conversion occurring in the Nordic Seas. A series of RAFOS floats and a profiling mooring were deployed in June 2010. In 2011 we recovered the mooring, deployed a new one and deployed a new series of floats. Final recovery of the mooring occurred in September 2012. Analysis of data from both moorings is underway, but a preliminary look at the data confirms the importance of eddies in fluxing warm, salty Atlantic waters from the boundary while continuously restratifying the basin. We expect to present initial results at the EGU meeting in Vienna in 2013.

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

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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 2012 included on-going processing and analysis of data obtained thus far, servicing the moored array and occupying the hydrographic section aboard *R/V Knorr* (Kn208, August 15-29), and continuing to write up results for journal publication. Finalized mooring and cruise data sets available to date have been submitted to the *OceanSites* data archive; data are also available on our project web site: http://www.whoi.edu/science/PO/linew/index.htm.

Recent Results

(1) During the 2008-10 setting of the Line W Moored Array, the Gulf Stream experienced a large southward meander for about two months. As observed previously during the SYNOP study and described by Savidge and Bane (JGR-1999), a strong deep cyclonic flow was spun up by this meander, resulting in a huge equatorward pulse of intermediate and deep water transport through the Line W array (see figure below). We believe much of this added equatorward flow returned poleward in the offshore limb of the deep cyclone, but that flow was beyond the moored array.

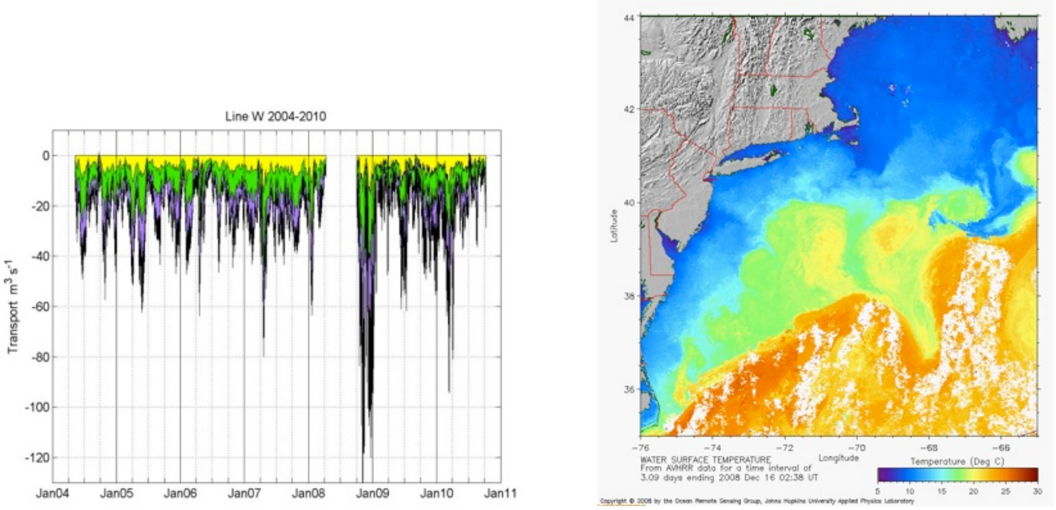

Fig. 1. Left: Time series of equatorward DWBC transport through the Line W moored array. Colors denote contributions by Upper Labrador Sea Water (yellow), Classical Labrador Sea Water (green), Iceland-Scotland Overflow Water (purple) and Denmark Strait Overflow Water (black). Following Toole et al. (DSR, 2011) extended through the 2008-10 array setting. Right: Composite Sea Surface Temperature image for mid-December 2011: time of the strong equatorward pulse of intermediate and deep waters.

(2) UK collaborator S. Elipot took the lead writing up an analysis of bottom pressure measurements along Line W and to the north. Strong coherence of bottom pressure fluctuations along the continental slope is observed. Also, a technique for using bottom pressure data spanning a continental slope to infer net basin-wide horizontal transport was explored jointly with the Line W mooring data (see bibliography).

(3) UK collaborator J.A. Brearley took the lead in a joint analysis of satellite altimeter and Line W hydrographic data that yielded a two-decade-long time series of upper-1000-m Gulf Stream transport. The time mean transport, annual cycle, and interannual variations are investigated (see bibliography).

(4) A Gulf Stream Warm Core Ring was bisected during the September 2009 Line W cruise. Direct velocity observations from the ship (ADCP) and one of the Line W moorings documented a near-inertial wave packet seemingly trapped in the vorticity bowl of the Ring, with wave phase lines closely following the bowed isopycnals of the Ring. PI T.M Joyce led the write up of these findings (see bibliography).

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Improving Interannual Prediction Skill in a Changing Climate via the Identification of Compensating Coupled Model Errors

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This project uses *transfer functions* to estimate the frequency-dependent and model-dependent characteristics of specific processes involved in AMOC. The transfer function, a tool borrowed from control engineering, describes how a response variable (e.g., AMOC strength) depends on particular inputs, as a function of frequency. This tool is well-suited to exploring why different models exhibit such different spectral characteristics of AMOC variability, with some models showing clear peaks in the power spectra, while others do not. Evaluating processes across multiple models helps identify what processes are robust, and which are not, across models.

Recent Results

The response of AMOC strength to surface forcing has been evaluated in eight models from CMIP3 and CMIP5, with a particular focus on CCSM4 and GFDL CM2.1; these are chosen because they exhibit such different spectral behavior. Transfer functions are evaluated from surface temperature, salinity, and wind stress, to the AMOC strength, defined by the projection onto the first EOF. There is very little agreement between models for any of the pairs of variables considered, suggesting the existence of systematic model errors, and that considerable uncertainty in the simulation of AMOC in current climate models remains. However, a robust feature of the frequency-domain analysis is that models with spectral peaks in their AMOC correspond to those in which AMOC variability is more strongly excited by high-latitude surface perturbations that have periods corresponding to the frequency of the spectral peaks. This helps explain why different models exhibit such different AMOC variability, however, it remains to understand why different models yield such different degrees of AMOC excitation in these frequency bands. These differences would not have been evident without using a method that explicitly computes the frequency-dependence, rather than a priori assuming a particular functional form.

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Sensitivity of the Atlantic Meridional Overturning Circulation in a Strongly Eddying Ocean Model

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The objective of this program is to study the sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) in a strongly eddying ocean model. We are performing simulations with a global ocean model (Parallel Ocean Program) in both eddy resolving (0.1°; "$R_{0.1}$") and non-eddying (1.0°; "x1") resolutions to study the impact of explicitly resolving eddy transports on the AMOC.

Recent Results

In a comparison between the two model configurations, we studied the response of the AMOC with respect to anomalous freshwater input from the Greenland Ice Sheet (GrIS; Weijer et al. 2012). We found both quantitative and qualitative differences in the AMOC response: the "x1" displayed a rapid, O(yrs) decline in overturning strength, after which the adjustment leveled out. In contrast, we found the decline in the "$R_{0.1}$" case to be more gradual, as it occurred on decadal time scales, and eventually it exceeded the "x1" in overall MOC decline. We found similar qualitatively different response in measures of deep convection in the Labrador Sea. In a related experiment, we applied the freshwater flux over a broad swath of the subpolar North Atlantic, mimicking the traditional "hosing" approach. Surprisingly, the "x1" hardly showed any difference in response between the hosing experiment, and the experiment with a realistic distribution of freshwater supply around Greenland. But the response in the "$R_{0.1}$" model to hosing was considerably stronger. We therefore conclude that explicitly resolving the mesoscale eddy field, as well as applying GrIS melt with a realistic spatial distribution, is important for a correct AMOC response to surface freshening of the subpolar North Atlantic.

Current work includes the analysis of the AMOC response to an extreme 0.5 Sv freshwater release. In addition, we are forcing the model with surface heat flux anomalies with the goal to excite decadal time scale oscillations in the system.

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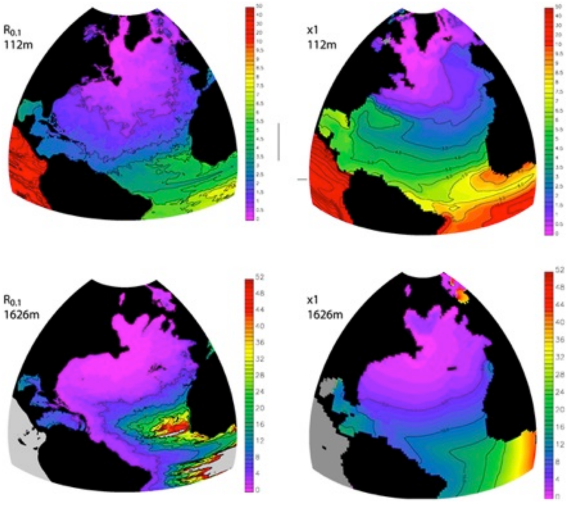

Figure 1. Arrival time (in years) for the dye in the strongly eddying "$R_{0.1}$" (left column) and non-eddying "x1" (right column) configurations, at depths of 112 m (upper panels; contours at 1-year intervals) and 1626 m (lower panels; contours at 5-year intervals). Grey denotes arrival times greater than 50 years.

Atlantic MOC Observing System Studies Using Adjoint Models

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Long-term goals

This project, now completed, exploited the existence of state estimation tools to understand the Atlantic circulation, including the meridional overturning circulation. The particular focus was on the observing systems, what they say about the circulation, and how they might be improved, using the method of Lagrange multipliers (adjoint method) developed in the independently supported ECCO-GODAE system.

Objectives and Work Completed

- Discussions of observing systems have been provided by Heimbach et al. (2010, 2011) and Wunsch (2010).
- Estimates of the meridional overturning circulation are described by Wunsch and Heimbach (2009, 2012).
- Related work, primarily within the ECCO-GODAE project, has brought close to fruition a system with a full Arctic and far more accurate sea ice sub-model. That system (ECCO version 4) will be the platform for significantly extending the study of the Atlantic circulation.
- The meridional correlations of the meridional overturning circulation for the 16 years of ECCO state estimate v3.73 have been studied by Wunsch (2010b) and which imply subtropical variations are fundamentally uncorrelated with those in the subpolar gyre, at least over the time period of the estimate. The same paper produces estimates of the linear prediction times of the MOC and SST in the western subpolar gyre.
- Impact of ocean surface advection processes in the evolution of sea surface temperature at seasonal and interannual timescales, relative to other factors such as mixing and surface heat exchanges (Vinogradova et al. 2012);
- Assessment of currently unobserved deep ocean variability and its potential impact on estimates of sea level, heat content and other quantities related to changes in the MOC (Ponte 2012a, b).

Impact and applications

The chief results are that with 20 years of observation, the AMOC is indistinguishable from a stochastic process - the result of numerous disturbances both internal (instabilities) and external (meteorological). Furthermore, over this duration, no useful coherence exists between subpolar and subtropical regions. Some linear predictive skill does exist, as a function of latitude, for the AMOC. Many processes, including a very strong annual cycle, inferred mixing coefficients, assumptions about space/time correlations, influence estimates of AMOC changes, and potential predictability. Design of a long-term measurement system needs to proceed on the basis of the existence of a multiplicity of physical regimes and time-scales.

Project information online: http://ecco-group.org

Publications

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

Period: December 1, 2011-November 1, 2012
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Collaborator: Tong (Tony) Lee[2]
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Graduate assistant: Feili Li and Weiwei Zhang

The objective of this project is 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 DOC and subsurface thermal structure estimated from satellite multi-sensor data.

Recent Research Results

A dipole pattern of the sea surface height anomaly in the North Atlantic: 1990s–2000s (Li et al. 2012a): A dipole pattern measured by satellite altimetry was analyzed. We found that the dipole pattern is mainly associated with the interannual to decadal SSHA oscillations of the two regions, which are 180 out of phase with each other over the time span of this study. The low-frequency variations of the SSHA in the subpolar region are strongly inversely correlated with the cumulative North Atlantic Oscillation (NAO) index (r = 0.84), in contrast with the Gulf Stream region, which is positively correlated (r = 0.22). This therefore reveals an asymmetric response of the regional SSHA to the cumulative NAO-forcing, in which the subpolar variability leads that of the Gulf Stream region by 29 months. Moreover, there is a remarkable reversal of the SSHA trends from the 1990s to the 2000s, which is unexpected given a weak and fluctuating NAO behavior since mid-1990s. Such SSHA variations in the 2000s might be related to the lagged variations of the Atlantic meridional overturning circulation (AMOC).

Linear and Nonlinear Sea Level Trends at Different Time Scales in the North Atlantic (Jo et al. 2012): In order to understand the different time scales in SSHA variability, the data were decomposed into seasonal, annual, interannual, decadal and residual signals using Ensemble Empirical Mode Decomposition (EEMD). First, the relative contributions of the decomposed SSHA time series to SLT were estimated. Although SSHA in the decadal scale have the largest contribution to SLT, SSHA in the interannual scale is also comparable in certain areas. Second, using the EEMD residual the nonlinear SLT was determined, which shows the turning point of the SLT during either the rising or falling trend. While a downswinging inflection was the dominant pattern in the regions of sea level rise occurring after 2007 in the Subpolar Gyre, the Subtropical Gyre, and the Equatorial Current, a pattern of upswinging inflection was dominated in the regions where sea level was significantly decreasing after about 2000 close to the North Atlantic Current and Northern Recirculation Gyre. We may therefore understand whether sea level changes in different regions are in phase or out of phase, and with how much lag.

Characteristic Features of the Sea Surface Height Anomaly in the North Atlantic from Altimeter Observations, (Li et al. 2012b): The sea level variations in the North Atlantic subpolar gyre (SPG) are dominated by the annual cycle and the long-term increasing trend. In comparison, the SSHA along the Gulf Stream (GS) is dominated by variability at intra-seasonal and annual timescales. The sea level rise in the SPG developed at a reduced rate in the 2000s compared to rates in the 1990s, which was accompanied by a spectral energy regain starting from around 2002 after a period of energy loss in the system. This rate reduction, as well as energy regain, is associated with changes in low frequency SSHA oscillations, revealing the importance of low frequency variability in the SPG. To identify contributing factors for these changes, the heat content balance (equivalent variations in the sea level) in the SPG 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 on an annual timescale. The low frequency variability in the SPG might be related to the deep ocean convection (DOC) process and the propagation of the Atlantic meridional overturning circulation (AMOC) variations between high- and mid-latitudes.

Lateral Heat Exchange after Deep Convection in the Labrador Sea (Zhang and Yan 2012): We focus on the Labrador Sea restratification after deep convection in the 2007–2008 winter. A regional model is configured, and is subjected to 6-hourly atmospheric forcing. A realistic cyclonic boundary circulation in the Labrador basin is reproduced, with a seasonal EKE field in line with altimeter observations. The IRs' thermal structures transform from boundary-current-like structures to those more similar to ambient water upon dissipation and their radii reduce to half the maximum (20 km) within 50 days. The IRs do not directly enter the convection area, but can maintain high stratification in its vicinity. Heat contents of the upper and lower layer have different trends thus different restratification mechanisms. The surface heat flux is responsible for 75% of the surface layer heat regain, while the lower layer heat regain can be attributed to lateral mixing by eddies. Since IRs do not transport heat directly into the convection region, theoretical restratification time scales by BCEs and CEs are estimated, and each type can recover the heat loss of the lower layer (200 – 1000 m) within 0.68 – 0.76 years and 2.8 years respectively. The restratification time scale of BCEs alone is in line with the observations, therefore, we conclude that BCEs are major players in restratification after deep convection, while IRs enhance the strength of BCEs by maintaining strong stratification around the convection area.

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Have Aerosols Caused the Observed Atlantic Multidecadal Variability?

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The objective of this research is to understand whether aerosol is a prime driver of the observed 20th century Atlantic multidecadal variability.

Key Results

The recent paper (Booth et al. 2012) showed that the HadGEM2-ES2 climate model closely reproduces the amplitude and phase of the observed multidecadal variations of area-averaged North Atlantic sea surface temperature (NASST) in the 20th century. The multidecadal variations simulated in HadGEM2-ES are primarily driven by aerosol indirect effects that modify net surface shortwave radiation. Hence Booth et al paper concluded that aerosols are "implicated as a prime driver of twentieth-century North Atlantic climate variability". We analyzed the HadGEM2-ES all forcing historical ensemble simulations and showed that there are important discrepancies between the HadGEM2-ES simulations and observations. We also analyzed the "Constant Aerosol" historical ensemble simulations of HadGEM2-ES, and shows that those important discrepancies are mainly due to the aerosol effects (Figure 1). These discrepancies cast considerable doubt on the above main conclusion of Booth et al. 2012 paper. The observed Atlantic Multidecadal variability is more consistent with the mechanism associated with the AMOC variability.

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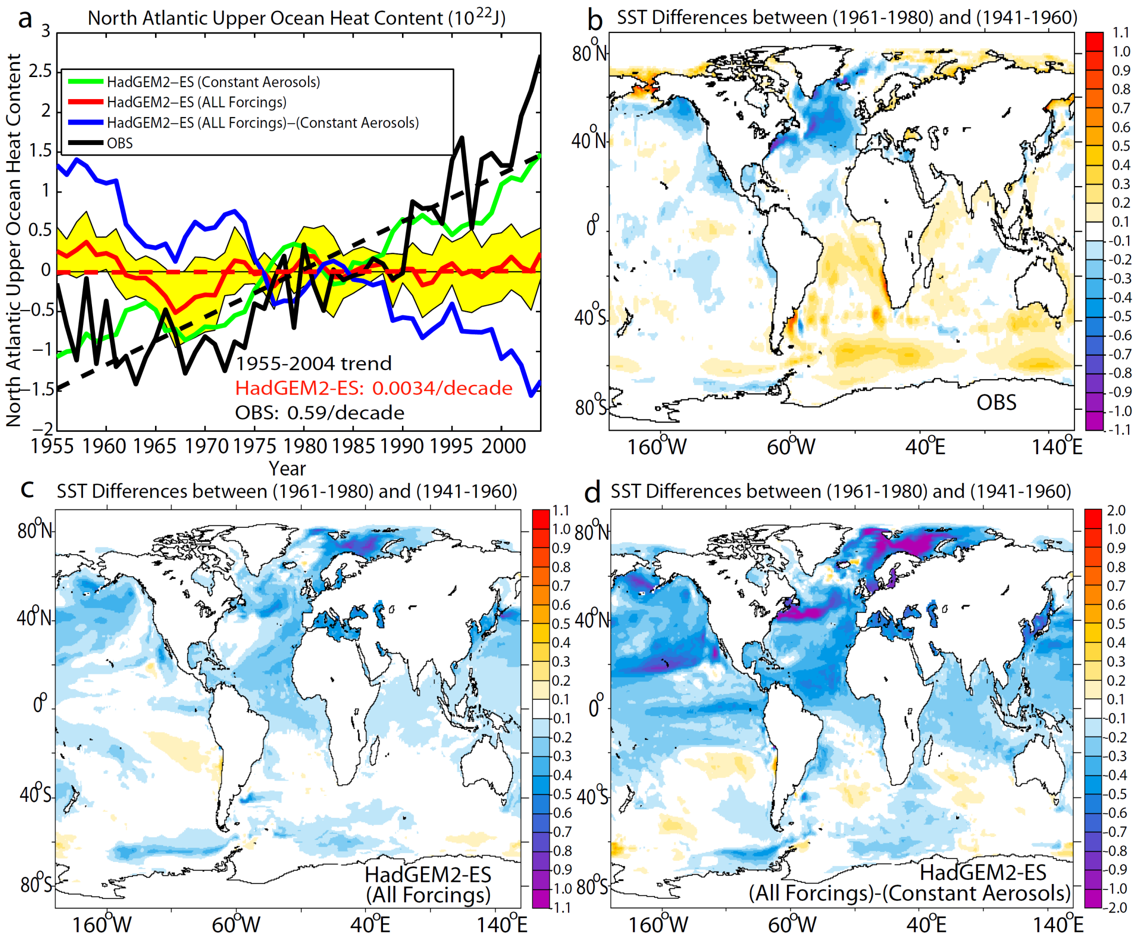

Figure 1. Discrepancies between observations and the HadGEM2-ES model simulation used in B12. (a) Area-averaged North Atlantic upper ocean heat content anomaly (0–700m, 75-7.5ºW, 0-60ºN) from HadGEM2-ES (Red: ensemble mean from historical simulation with all external forcing ("ALL Forcings"). Yellow shading: 1 std of ensemble spread of "ALL Forcings". Green: ensemble mean from "Constant Aerosols" historical simulation. Blue: ensemble mean difference between "ALL Forcings" and "Constant Aerosols". Black: observations, relative to 1955-2004 mean. The dash lines in (a) are linear trends for the respective shown variables. (b,c,d) SST differences between the North Atlantic cold period (1961-1980) and the North Atlantic warm period (1941-1960). (b) Observation (c) HadGEM2-ES "ALL Forcings" ensemble mean (d) Ensemble mean difference between HadGEM2-ES "ALL Forcings" and "Constant Aerosols".

Simulated Climate Impacts of the Nordic Sea Overflow in a High Resolution Global Coupled Climate Model

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The objective of this research is to study the atmospheric response to the changes in the Nordic Sea overflow.

Key Results

A perturbed experiment is conducted for 40 years using the GFDL high resolution global coupled climate model CM2.5, in which a steady strong Nordic Sea overflow is maintained. In contrast, the Nordic sea overflow is very weak in the control experiment. The averaged difference between the perturbed and control experiments is calculated to analyze the atmosphere response to changes in the Nordic Sea overflow. The results show a robust quasi-steady oceanic response, i.e. a stronger and deeper-penetrating Nordic Sea overflow leads to warmer SST east of Newfoundland and colder SST south of the Grand Banks, i.e. a dipole SST anomaly. The dipole SST anomaly in the extra-tropical North Atlantic excites an atmospheric sea level pressure (SLP) response, which resembles the East Atlantic Pattern (EAP). The dipole SST anomaly also induces a dipole anomaly in precipitation, evaporation and surface heatfluxes. A stronger and deeper-penetrating Nordic Sea overflow also induces a dipole anomaly in the low cloud liquid water content with potential impacts on marine fog, as well as a warm anomaly in surface air temperature (SAT) over the North America. The atmospheric response also includes significant changes in the vertical motion across the fronts of the Gulf Stream and the North Atlantic Current.

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