2013 US AMOC SCIENCE TEAM ANNUAL REPORT ON PROGRESS AND PRIORITIES

US CLIVAR
Climate Variability & Predictability

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COVER IMAGE:

Components of the AMOC observing system; Credit: Jack Cook, Woods Hole Oceanographic Institution

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Executive Summary

The US AMOC program was established in 2008 to develop an improved understanding of the Atlantic Meridional Overturning Circulation (AMOC), which was identified as a key near-term priority in the 2007 Ocean Research Priorities Plan issued by the Joint Subcommittee on Ocean Science and Technology (JSOST, now SOST). A five-year implementation strategy for the US AMOC program was developed in October 2007 by a panel of scientists, outlining the program goals and the initial components of an AMOC monitoring system and AMOC prediction capability. A US AMOC Science Team, comprised of funded investigators, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies (NASA, NSF, NOAA, and DOE). The report herein is the sixth annual progress report submitted by the US AMOC Science Team. The purpose of this report is to summarize progress in the past year on the main objectives of the program, identify any programmatic gaps, and make recommendations on near-term research priorities for the program.

Planning activities within the US AMOC program continue to be organized under four Task Teams, consisting of groups of program principle investigators (PIs), each led by a volunteer chair and vice-chair. The task team leaders, together with the Science Team chair, form the US AMOC Program Executive Committee. In June 2013, Gokhan Danabasoglu became the new chair of the Science Team after Bill Johns stepped down. During this transition, there were several changes in the Task Teams' leadership positions. A list of current leadership positions is as follows:

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

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

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

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

The US AMOC Program Executive Committee provides overall program guidance and liaises with the US 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 A, along with the current membership of each Task Team.

Meetings of the Science Team have been held annually since 2009. In 2011 and 2013, these meetings were held jointly with the UK RAPID-WATCH program in Bristol, England and Baltimore, Maryland, respectively, as joint science conferences. This joint meeting arrangement will continue in the future, with a joint US AMOC/ RAPID-WATCH science conference to be held in alternate years and a national Science Team meeting held in intervening years. The next Science Team meeting will be held in Seattle, Washington on September 9-11, 2014, hosted by the University of Washington. The next joint meeting will be in Bristol, England in 2015.

An external review of the US AMOC program was conducted during 2012 with the review report finalized in June 2013. The report is very positive, stating that the US AMOC program is successful, impressive, and stimulating. The external review committee made several recommendations to improve the program, and the Executive Committee has progressed with implementing recommended changes.

As reflected in the Task Team structure, the US AMOC program has four main objectives:

1. AMOC observing system implementation and evaluation;
2. An assessment of AMOC state, variability, and change;
3. An assessment of AMOC variability mechanisms and predictability; and
4. An assessment of the role of AMOC in global climate and ecosystems.

Progress on these main program objectives during 2013 is summarized in section 2 of this report. As indicated above, a national Science Team meeting to review progress toward near-term priorities of US AMOC was not held in 2013. However, each Task Team held a teleconference with their members to discuss their team's progress towards program goals, revisit their near-term priorities and long-term goals, and identify science gaps, giving consideration to the presentations and discussion at the 2013 International Science Meeting. Although a major review and possible revisions of the near-term research priorities (section 3) will be one of the discussion items in the 2014 Science Team meeting, they are modestly modified in this report to reflect outcomes of the Task Team teleconferences.

Summarized below are a few highlights of the accomplishments of the program:

1. NSF approved the proposal of the overturning in the subpolar North Atlantic program (OSNAP) led by Lozier et al. in September 2013. OSNAP is designed to provide a continuous record of the full water column, trans-basin fluxes of heat, mass, and freshwater in the subpolar North Atlantic. It is planned for deployment in mid-2014, with an initial planned lifetime of four years. It consists of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West), and the second from the southeastern tip of Greenland to Scotland (OSNAP East).
2. An emerging focus is on developing a trans-basin South Atlantic observing system, with support from US and international partners. A core initial piece, the US AMOC Southwest Atlantic MOC (SAM) project has now collected more than four years of data, and it has been redeployed with batteries that will last through 2016. Initial results using 20 months of data suggest that the variability of the basin-wide AMOC at 34.5°S is of comparable magnitude to that observed in the longer 26.5°N record.
3. Work towards establishing a full Atlantic-wide monitoring system continued in 2013 with the maintenance of various pieces in the SAM, the subtropical Atlantic (mooring arrays at 16°N, 26.5°N, 39°N, and the Oleander section), the North Atlantic subpolar gyre, and the gateways to the Arctic (Davis Straits and Norröna Section). A focus this year was the derivation of associated heat and freshwater (or salinity) transports. Another ongoing effort is the development of synthesis frameworks to combine the diverse pieces of the observing system into a dynamically consistent Atlantic-wide state.

4. Various AMOC fingerprints have been identified and shown to be a useful tool for reconstructing past AMOC variations. It has been shown that AMOC variations at high latitudes precede AMOC fingerprints by several years, providing the physical understanding of why a stronger/weaker AMOC can lead to warming/cooling in the subpolar gyre by several years, and contribute to the enhanced decadal prediction skill in ocean temperatures in the subpolar gyre.
5. It is found that the typical estimation of AMOC in depth space is not suitable at mid and high latitudes. For studies of subpolar AMOC variations or their meridional connectivity with those in the subtropics, AMOC variations need to be estimated in density space, instead of depth space. AMOC variations estimated in density space reveal significant meridional coherence (especially between the subpolar and subtropical regions).
6. Using a variety of observations including altimetry as well as a variety of different models, a high degree of meridional coherence is found in meridional heat transport (MHT) from 30°S to 40°N, and the increased (decreased) MHT corresponds to increased (decreased) heat loss. Good agreement was found with the MHT estimates from the RAPID/MOCHA program. Efforts continued to estimate the mean and the variability in the MHT and MOC in the South Atlantic and their linkages to MOC and MHT in the North Atlantic. The relationships between modeled MOC intensity and MHT in various models are compared to observations.
7. The mechanisms and time scales of the AMOC remain largely model-dependent in both coupled and ocean–sea ice models. This has implications for the predictability limit of the AMOC and its associated climate impacts. Some mechanisms involving buoyancy forcing in the Labrador Sea or the westward propagation of subsurface Rossby waves appear to be key in driving AMOC variability, though their robustness across models remains to be shown.
8. Change in AMOC strength is an important factor in sea level changes in the North Atlantic. In AMOC and sea level changes, injection of melt water into the North Atlantic plays a major role, and heat transport associated with AMOC into the Greenland Ice Sheet is an important contributor to its melting.
9. Analysis of Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5) model simulations indicate that the surface expression of AMOC variability – the so-called Atlantic Multidecadal Oscillation (or Variability) – remains unchanged with both the past and the expected 21st century changes in greenhouse gas concentrations.

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

1 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 interagency program to develop the initial components of an AMOC monitoring system and AMOC prediction capability.

In response to this implementation plan, the supporting agencies (NASA, NOAA, and NSF) created a US AMOC Science Team in March of 2008, which has been expanded in subsequent years. In late 2011, DOE was added as a contributing agency, and several new PIs from AMOC-related DOE projects have joined the Science Team. This Science Team, comprised of all PIs designated by the funding agencies that are performing research relevant to the US AMOC program, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies.

As one of its responsibilities, 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 US AMOC efforts, including the identification of evolving science and monitoring issues.

In October 2012, US AMOC completed its fifth year as a SOST priority and provided a final report on the achievements and remaining challenges in advancing the understanding of the AMOC. The four sponsoring agencies confirmed their commitment to continue forward with the US AMOC Science Team within US CLIVAR in order to fulfill the goals of the program.

The report herein is the sixth annual progress report submitted by the US 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.

1.1 2013 US AMOC/UK RAPID International AMOC Science Meeting

Meetings of the Science Team have been held annually since 2009. In 2011 and 2013, these meetings were held jointly with the UK RAPID-WATCH program in Bristol, England and Baltimore, Maryland, respectively, as joint science conferences.

The 2013 International Science Meeting, "AMOC Variability: Dynamics and Impacts," convened July 16-19. The meeting scientific organizing committee was comprised of US AMOC and UK RAPID scientists: co-chairs James Carton of the University of Maryland and Stuart Cunningham of the Scottish Association for Marine Science, with members Eleanor Frajka-Williams of the UK National Oceanographic Centre, Young-Oh Kwon of the Woods Hole Oceanographic Institution, David Marshall of the University of Oxford, and Rym Msadek of the NOAA Geophysical Fluid Dynamics Laboratory.

The meeting was well attended by more than 100 scientists from US and international academic and research institutions who shared research findings on variability on seasonal-to-interannual and decadal-to-centennial timescales, as well as the impacts of AMOC on sea surface temperatures (SSTs), regional climate, regional sea level rise, and carbon/biogeochemistry. Future perspective talks helped motivate discussion and identification of the following set of international collaborative research needs:

- Faster real time availability of RAPID data
- Adoption of new technologies as they mature (for example, autonomous gliders) to sustain the monitoring arrays over many decades
- Development of proxies of AMOC variability using long records of sea level, SST and paleo data
- Development of data assimilation and other estimation techniques to combine available oceanic and meteorological observations in ways consistent with the equations governing the two systems
- Testing of variability mechanisms in models
- Understanding of the impact of ocean model biases in coupled model simulations
- Identification of similarities and differences between the AMV in the historical record, the corresponding variability in coupled climate models, and their relationships to AMOC
- Exploration of the role of aerosol forcing in impacting the climate of the North Atlantic sector
- Investigation of AMOC variability and biogeochemistry/carbon sequestration

A meeting summary, prepared by the scientific organizing committee, is in press in the Bulletin of the American Meteorological Society. Meeting presentations are available at http://www.usclivar.org/meetings/amoc2013-agenda. The science results presented at the meeting and the list of research needs identified above have informed the subsequent US AMOC Task Team discussions of revised near-term priorities.

Annual meetings will continue in the future, with a joint US AMOC/UK RAPID science conference to be held in alternate years and a national Science Team meeting held in intervening years. The next Science Team meeting will be held in Seattle, Washington on September 9-11, 2014, hosted by the University of Washington. The next joint international meeting will be in Bristol, England in 2015.

The US AMOC Science Team would like to thank the scientific organizing committee for their volunteer efforts to plan and convene the successful international meeting in 2013.

1.2 External Review of the US AMOC Program

An external review of the US AMOC program was conducted during 2012-2013. The review committee members were Lynne Talley of the Scripps Institution of Oceanography, Galen McKinley of the University of Wisconsin-Madison, and Noel Keenlyside of the University of Bergen. All three members of the review committee were knowledgeable in the science, methods, and challenges of studying the Earth's meridional overturning circulation and none of them received funding as part of the US AMOC program. The committee was charged with: i) evaluating the adequacy of science planning: the goals and objectives of the program, implementation: success and impediments toward achieving goals and objectives, and synthesis: achieving synthesis of results beyond individual projects; ii) identifying needs and opportunities for future research directions and implementation approaches; iii) preparing a written report summarizing its evaluation findings; and iv) presenting the report to the US AMOC Science Team. The committee informed its review by attending the 2012 US AMOC Science Team Meeting, reviewing the implementation plan and annual progress reports, and surveying members of the Science Team, the Executive Committee, and agency program managers. The committee submitted its final report on June 21, 2013, and the report was presented to the US AMOC Executive Committee at the July 2013 Baltimore meeting.

The review report is very positive in its assessment of the US AMOC program objectives, structure, and progress. The executive summary of the report summarizes the findings of the committee as such:

> "The US CLIVAR Atlantic Meridional Overturning Circulation (AMOC) program is successful, impressive, and stimulating. It is producing major innovations and discoveries around a major scientific topic - the mechanisms and variability of the overturning circulation in the Atlantic and its interaction with other climate elements. The science is relevant to a large community of climate scientists and policy makers. The presence of a large cohort of scientists at the US AMOC meeting, and the alternation of the meeting between the US and its international partners, are indications of the viability, strong science, and enthusiasm around this program.
>
> The unique interagency funding structure that supports the US AMOC program is strongly commended, with excellent communication between the funding managers in the several agencies that support US AMOC (NSF, NASA, NOAA, DOE), and with the US CLIVAR Project Office. The creation of this large program from individually funded proposals in the absence of the desired targeted federal funding is commended. This structure is mostly transparent and flexible."

The external review committee report has also made several recommendations to further improve the US AMOC program. These recommendations include concerns with adequacy of funding; improving communication with new PIs, i.e., science team members; expanding and updating the web presence; formalizing leadership rotation procedures; and setting long-term goals in addition to near-term priorities, by actively seeking input from the science team members and encouraging more discussion. Several of the committee recommendations have been already adopted, such as formalizing leadership rotation procedures, having task team teleconferences to improve communication, and hosting the 2014 Annual Meeting near a university (University of Washington). Next steps will include a discussion of the external review committee report with the broader Science Team at the 2014 Seattle meeting.

The US AMOC Science Team would like to thank the external review committee members for their dedicated and diligent efforts.

2 PROGRESS ON PROGRAM OBJECTIVES

2.1 Existing and Approved Observational Programs

An understanding of basin-wide Atlantic Ocean circulation variability remains a challenge and prerequisite for skillful seasonal to inter-annual (or even decadal) prediction. Various elements of an observing system have been in place for several years, or are planned for deployment. This section summarizes available and planned observational assets, discusses recent results obtained and notes challenges for obtaining a complete picture of the time-evolving, three-dimensional circulation.

Subtropical North Atlantic

Several projects are tasked with continuous monitoring of the strength and structure of the AMOC and its associated heat transport:

- "An Observing System for the Meridional Overturning Circulation and Ocean Heat Transport in the Subtropical North Atlantic," led by Johns et al., estimates meridional heat transports using the UK-US RAPID-MOCHA trans-basin array of 22 moorings deployed at 26.5°N, which has collected data for nearly a decade since being established in 2004.
- "Western Boundary Time Series (WBTS)" led by Baringer et al., continuously monitors the northward flowing Florida Current and the southward flowing Deep Western Boundary Current (DWBC), and has been nearly continuous since 1982.
- "The Oleander Project: Sustained observations of ocean currents in the Northwest Atlantic between New York and Bermuda," led by Donohue and Rossby, has collected weekly ADCP and monthly XBT measurements since 1992 from container vessel CMV Oleander, which operates on a weekly schedule between New Jersey and Bermuda.
- "Meridional Overturning Variability Experiment (MOVE)," led by Send and Lankhorst, maintains a system of moorings and bottom sounders to continuously sample the strength of the lower branch of the AMOC at 16°N between the western boundary and the mid-Atlantic ridge since 2000.
- "Line W: A Sustained Measurement Program Sampling the North Atlantic DWBC and Gulf Stream at 39°N," led by Toole et al., documents inter-annual transport changes in the North Atlantic's DWBC and Gulf Stream, since 2004, using data from a sustained moored array and repeated occupation of a hydrographic section.

The NOAA State of the Climate 2013 report (Baringer et al. 2013) summarizes meridional heat and volume transports at 41°N, 26°N, 16°N, and 35°S. The 26°N array (RAPID/MOCHA/WBTS) time series suggest a statistically significant downward trend in the AMOC from 2004 to 2012 (Smeed et al. 2013). In contrast, an extended estimate based on a model-data synthesis covering the period 1992 to 2010 shows no significant trend (Wunsch and Heimbach 2013a). Ocean heat content in the subtropical gyre north of the 26°N line shows a marked decrease in late 2009, coincident with the downturn in heat transport across 26.5°N (Cunningham et al. 2013). The heat transport divergence between 26.5°N and 41°N can approximately explain the magnitude and timing of this event. Essentially all of the inter-annual variability that has occurred in the meridional heat transport is contained in the overturning component of the heat transport, while the gyre component has maintained a stable mean value.

Extended Florida Straits measurements include inference of salinity transports from cable measurements (Szutz and Meinen 2013) and coherence analysis of Florida Current volume transport and the Antilles Current offshore of the Bahamas (Frajka-Williams et al. 2013). This analysis is based on data from WBTS and altimetry.

Further north, the Oleander data shows no evidence of a decrease in Gulf Stream transport, in contrast to recent claims of a Gulf Stream slow-down (Rossby et al. 2014). A detailed comparison between Oleander-derived sea surface height and the AVISO sea surface height products show excellent agreement between the two systems.

Subpolar North Atlantic and Arctic

Arctic and subarctic regions have been or will be covered by the following projects:

- "The Arctic Observing Network at Critical Gateways—A Sustained Observing System at Davis Strait," led by Lee et al., employs a now decade-long system of moorings, annual (autumn) hydrographic sections, and autonomous gliders to quantify exchanges between the Arctic and Subarctic North Atlantic through the Canadian Arctic Archipelago (CAA).
- "OSNAP: Overturning in the Subpolar North Atlantic Program," led by Lozier et al., is a new program designed to provide a continuous record of the full water column, trans-basin fluxes of heat, mass, and freshwater in the subpolar North Atlantic through deployment of fixed current meter arrays, repeat hydrographic occupations, and glider surveys. The project, funded by NSF in September 2013, is planned for deployment in mid-2014, with an initial planned lifetime of four years. It consists of two legs: one extending from Southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West), and the second from the southeastern tip of Greenland to Scotland (OSNAP East). The network also includes subsurface floats (OSNAP Floats) in order to trace the pathways of overflow waters.
- "The Norröna Section," led by Rossby and Flagg, monitors the strength and structure of the Atlantic inflow into the Nordic Seas between Scotland, the Faroes, and Iceland via repeat ADCP measurements onboard the ferry MF Norröna.

Observations at Davis Strait show large interannual variability in volume and freshwater transports, with no clear trends observed between 2004-2010 (Curry et al. 2013). However, changes in circulation have occurred, as freshwater outflow from Baffin Bay has decreased and warm, salty North Atlantic inflow has increased since 1987-1990. Large-scale atmospheric teleconnections, such as the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO), correlate poorly with Davis Strait volume transport. Efforts have also focused on attributing salinity transports associated with the Davis Strait outflow (Jackson et al. 2014). The first year-round occupation of an Arctic region by autonomous gliders was achieved by linking two missions with a service interval in February in a narrow, ice-free region in the eastern Strait. This includes five months of operations beneath sea ice and two months in marginal ice conditions.

A first report, published by Rossby and Flagg (2012), presented initial volume and heat transport and hydrographic estimates that were used to infer heat supply magnitudes and pathways to the Nordic Seas.

South Atlantic

The following US-led project covers elements of the South Atlantic circulation:

- "Southwest Atlantic MOC project (SAM)," led by Meinen et al., is designed to measure both the warm-upper and cold-deeper flows associated with MOC near the western boundary at 34.5°S. The array has now collected more than 4 years of data and it has been completely recovered and redeployed with batteries that will last through 2016. Additional deployments by Brazilian (doubling number of moorings), French, and South African (eastern boundary array) partners contribute to the developing trans-basin array at 34.5°S.

Initial results from the SAM array show a highly variable DWBC at 34.5°S, with volume transport variations of more than 40 Sv occurring on time scales of a few days and anomalies of more than 20 Sv persisting for several months (Meinen et al. 2012). Comparison to 27-years of output from the high-resolution ocean general circulation model for the Earth Simulator (OFES) indicated 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. The initial 20 months of SAM data, coupled with data from a parallel French array on the African continental slope, suggest that the variability of the basin-wide MOC at 34.5°S is of comparable magnitude to that observed in the longer 26.5°N record (Meinen et al. 2013). The variations at 34.5°S are driven roughly evenly by changes on the western and eastern boundaries for time scales resolved by the 20-month record.

Data repositories

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

NOAA Florida Current (FC) and cruise data: http://www.aoml.noaa.gov/phod/wbts/data.php

FC and cruise data merged with MOC data: http://www.rapid.ac.uk/rapidmoc/

FC and cruise data merged with Heat transport data: http://www.rsmas.miami.edu/users/mocha/

Oleander website: http://po.msrc.sunysb.edu/Oleander

Oleander data distribution: http://www.po.gso.uri.edu/rafos/research/ole

Line W: http://www.whoi.edu/science/PO/linew/

US Cooperative Arctic Data and Information Service (CADIS): http://www.aoncadis.org

NOAA instruments for SAM: http://www.aoml.noaa.gov/phod/research/moc/samoc

Norrsöna section data archive: http://po.msrc.sunysb.edu/Norrona/

MOVE array data website: http://mooring.ucsd.edu/projects/move/move_intro.html

ECCO-Production version 4 (1992-2011):

http://mit.ecco-group.org/opendap/ecco_for_las/version_4/release1/contents.html

2.2 An Assessment of AMOC State, Variability, and Change

The US AMOC program supports a variety of efforts designed to assess the physical state of the AMOC – that is, the rates of volume and heat transports 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. This section describes progress on these efforts as they pertain to the near-term research priorities described in section 3.

Observational results

Estimates of both the mean and the variability in the meridional oceanic heat transport (MHT) and MOC in the South Atlantic, and its linkages to MOC and MHT in the North Atlantic, have been a focus of the program over the last year. Goni and Dong computed and analyzed the time series of the geostrophic and Ekman components of the MOC and MHT between 20° and 35°S as estimated from altimetry observations and National Centers for Environmental Prediction (NCEP) winds. Preliminary results show that the geostrophic component dominates the interannual variability of MOC and MHT during 1993-2005, with the Ekman component playing a large role after 2005. The mean values of MOC (MHT) are 18.77 Sv (1.23 PW), 22.10 Sv (1.10 PW), 22.73 Sv (0.76 PW), and 23.06 Sv (0.72 PW) at 20°S, 25°S, 30°S, and 35°S, respectively. This analysis denotes an increase in MHT towards the equator. The time series exhibit a long-period variability with high values in the mid-2000s and low values in mid-1990s. Garzoli et al. examined the properties of MOC and associated MHT and salt fluxes in the South Atlantic, using data collected along 27 sections at nominally 35°S for the period of 2002 to 2011, and Argo profile data collected in the region. Baringer et al. extended this time series through 2013 and compared it to the ECCO2 State estimation model. Macdonald and Baringer (2013) compared the 35°S XBT derived MHT estimates to the estimates at 26°N and 41°N. These analyses show that the South Atlantic is responsible for a northward MHT with a mean value of 0.54 ± 0.14 PW. The MHT exhibits no significant trend from 2002 to 2011. Statistical analysis suggests that an increase of 1 Sv in the MOC leads to an increase of the MHT of 0.04 ± 0.02 PW. Estimates using data collected from three different kinds of observations, contrary to those obtained from models, feature a positive salt advection feedback. Their ongoing analysis includes estimating the differences between in situ heat transport estimates and model-based estimates. In addition, they are extending observational estimates to include satellite derived synthetic XBT profiles and monthly time series estimates starting in 1992 along 20°S, 25°S, 30°S, and 35°S. An expansion of this program could include the analysis of all in situ data (not just XBT data) to determine the physical processes involved in meridional heat and mass transports throughout the Atlantic Ocean.

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 and observational efforts to quantify the transport there are ongoing. Bower and Spall deployed an array of eight current meters in August 2010 to measure currents and water properties between the bottom and 500 meters. Deployed in collaboration with M. Rhein (University of Bremen), the array is designed to obtain an improved direct estimate of the mean and low frequency variability of the deep westward transport of Iceland-Scotland Overflow Water (ISOW) through the CGFZ and to gain a better understanding of the causes of the low frequency variability and the influence of ridge fracture zones on the larger scale oceanic circulation. The moorings were recovered in July 2012, and all of the data was processed in the past year. A preliminary calculation of the two-year mean and standard deviation of ISOW transport was -1.7 ± 1.5 Sv, compared to -2.4 ± 3.0 Sv reported by Saunders for a 13-month period in 1988-1989 using the same isohaline. The temperature and salinity time series also indicate large fluctuations in ISOW layer thickness. Bower and Spall are also developing a modeling effort focused on the complex circulation in the CGFZ.

The Dynamics of Abyssal Mixing and Interior Transports Experiment (DynAMITE) focused on quantifying the strength and structure of diapycnal mixing along the Mid Atlantic Ridge and the interior flows of North Atlantic Deep Water (NADW) through the western basin that result from that mixing. Curry and Polzin found that localized turbulent mixing alters the basin scale stratification and sets the deep layers in motion, contributing to the near-doubling of cold limb transports observed in the DWBC between Line W at 41°N (~15 Sv) and the RAPID array at 24°N (~30 Sv). Their results confirm the existence of an abyssal upwelling cell (AUC) that transforms approximately 8 Sv of cold, dense waters flowing northward at depths greater than 4000 m across the MOVE array at 16°N, into warmer, lighter density classes which are subsequently returned southward in the DWBC at depths between 2000-3500 m. The upwelling occurs primarily between 10°–38°N in the western basin, and the resulting lateral flows entrain into the DWBC in the vicinity of Cape Hatteras and the Bahamas. One of DynAMITE's central results is an updated view of the buoyancy-forced, interior circulation beneath the thermocline, which emphasizes the role of turbulent mixing, vortex stretching, and enhanced vertical diffusivities – as opposed to large-scale horizontal recirculations, advective timescales, and background diffusivity rates – to water mass transformation and buoyancy gain in the AMOC's cold limb. The DynAMITE array measured 5-6 Sv of interior NADW flows diverted equatorward around Bermuda Rise from the deep Gulf Stream. The AUC contributes the remaining flow to the boosted DWBC transports observed by the RAPID array. Entrainment of these interior flows into the western boundary contributes to the observed disconnection between AMOC variability measured at mid-latitudes (Line W, Labrador Sea) and the tropics (RAPID, MOVE).

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 sea surface height (SSH) in the gyre. 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. A collaborative investigation of the AMOC connections, both deep and shallow, between subtropics and subpolar gyre has been initiated with the HYCOM (Hybrid Coordinate Ocean Model) Atlantic model, with Xu and Chassignet. They are analyzing both the warm water pathway through the North Atlantic Current and the southward dense AMOC branch flowing from the Greenland-Scotland Ridge and Labrador Sea. They found a significant part of the overflow moves along interior pathways instead of along the western boundary, confirming the previous results of Bower et al. (2009). In a collaborative study, Eldevik and Langehaug continue with calculations of AMOC projected on potential temperature-salinity space using HYCOM simulations and observations. This formulation allows examination of the coupling between AMOC and water mass transformation through both internal mixing and air-sea freshwater and heat fluxes.

One of the primary reasons for investigation of the AMOC is its role in the northward transport of heat throughout the Atlantic Ocean. Kelly and Thompson investigate northward heat transport in the Atlantic using a variety of observations, including altimetry, and different models. They found a high degree of meridional coherence from 30°S to 40°N, and showed that increased (decreased) MHT corresponds to increased (decreased) heat loss. Good agreement was found with the MHT estimates from the RAPID/MOCHA programs. Zhang, Thompson, and Kelly showed that surface heating makes a substantial non-seasonal contribution in the subpolar gyre annual sea level changes and that the Sverdrup Balance, with weak modification by topography, explains much of the intergyre variability on annual time scales. They also find that the principal pattern of variability of MHT on interannual times scales is symmetric about the equator. This result is consistent across multiple model simulations in both a hindcast simulation of the last 50 years as well as five different historical coupled climate model simulations from the CMIP5 archive. The pattern has significant skill up to 20°N suggesting that the variability even at the latitude of RAPID/MOCHA may be of tropical origin. They find that throughout much of the North Atlantic, SSH is lagged correlated with surface turbulent heat flux by several months. Performing the same analysis using SST rather than SSH, shows that SSH has more predictive skill for surface turbulent heat fluxes than does SST. Zhang, Thompson, and Kelly find that the eighteen-degree water regions exert the strongest control on air-sea turbulent heat fluxes, indicating that the stored heat anomalies in the mode water can force changes in the atmosphere.

Shum, Kuo, Yi, and Rashid continue with their efforts to estimate AMOC variability using satellite observations of SSH 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. They have generated a decadal (1996–2010) time series of surface and subsurface currents using multiple radar altimetry (ERS-1/-2 and ENVISAT) and XBT/Argo hydrography data, showing the present-day evolution of AMOC. Data products will be available to the scientific community in the near future.

In another study, Yan and Jo used satellite altimeter observations of SSH to investigate sea level trends in the subpolar and subtropical gyres 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 deep ocean convection processes and the propagation of the AMOC variations between high- and mid-latitudes. Jo et al. also investigated the linear and nonlinear sea level trends at different time scales in the North Atlantic. 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 stratification around the boundary current area. The dominant modes of variability in the temperature and ocean heat content of the central Labrador Sea were also investigated using the Hilbert-Huang Transform (HHT) based on collected Argo profiles. The interannual signals in the Labrador Sea, at especially the intermediate layers, are attributed to the deep convective processes influenced by both oceanic and atmospheric conditions. Over longer timescales, underlying warming trends from a nine-year record might be part of multi-decadal variations that reflect the Atlantic Multi-decadal Variability (AMV).

The ISOW supplies approximately a third of the NADW, which is the major artery of the deep limb of 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. Glider sections across the ridge show intense mixing of low salinity waters, which originate north of Iceland, exchange through mesoscale instability with the warm, northward flowing waters that turn east to form the Faros Current. The warm water is marked with low oxygen concentration, and its origins can be traced to the deep tropics. Temperature, salinity, and oxygen data show the mixing to occur primarily in winter, at the time when deep convection penetrates all the way down to the sloping front. Quantitatively, such mixing represents a significant contribution to the mixing of warm-branch waters as they form the Norwegian Current.

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. The project was extended into 2013 to investigate the dynamics and impact of strong wind events on the East Greenland shelf – another freshwater pathway into the North Atlantic subpolar gyre. These hurricane intensity downslope wind events advect cold air off the Greenland Ice Sheet resulting in disruption of sea ice flow along the East Greenland coast and in large buoyancy losses over the Irminger Sea.

Data assimilation models and synthesis

A long-term goal of the Estimating the Circulation and Climate of the Ocean (ECCO) project is the provision of dynamically and kinematically consistent global state estimates, using all available heterogeneous satellite and in situ data in combination with a state-of-the-art ocean model. A new generation global state estimate (ECCO-Production version 4), covering the period 1992-2011 has recently been produced and made available online. Initial studies provide an assessment of statistical properties of AMOC variability at various latitudes (Wunsch and Heimbach 2013a) and mode water formation globally and in the Atlantic (Speer and Forget 2013). The project “Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period,” led by Heimbach et al., takes advantage of accurate closure of property budgets (heat and freshwater) to understand the dynamics of low-frequency SST and upper ocean heat content variability in the Atlantic (Buckley et al. 2013) and their relationship to available atmospheric reanalysis products (Chaudhury et al. 2013, 2014).

Related to ECCO, the project “Collaborative Research: An eddy-permitting Arctic & Sub-Polar State Estimate for Climate Research (ASTE)” aims to produce an eddy-permitting coupled ocean—sea ice regional state estimate with an emphasis on the North Atlantic subpolar gyre and the Arctic. Following a regional feasibility study targeting the Labrador Sea and Baffin Bay (Fenty and Heimbach 2013a,b), the production of an eddy-permitting state estimate covering the ASTE domain is now under way.

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

Another effort involving ocean data assimilation to explore Arctic-Subarctic climate was led by Carton, Chepurin, Hakkinen, and Steele, who aim to develop improved understanding of past oceanic changes that have occurred at high latitudes by extending the Simple Ocean Data Assimilation (SODA) ocean reanalysis as a tool for high latitude research. They have begun development of hybrid sequential data assimilation filter, combining 3DVar and ensemble filters. They compared the tide gauge dataset with currently available ocean reanalyses and syntheses. They also investigated the role of decadal variations in aerosols on the ocean circulation through analysis of the CMIP5 coupled model responses to volcanic aerosols.

2.3 An Assessment of AMOC Variability Mechanisms and Predictability

Historical ocean state reconstructions continue to be a key tool for investigations of AMOC variability mechanisms on time scales from monthly to multi-decadal. The second phase of the Coordinated Ocean-ice Reference Experiments (CORE-II) effort, which defines a protocol for consistent forcing of ocean—sea ice model hindcasts over the time period from 1948 to 2007 coordinated by the CLIVAR Working Group on Ocean Model Development, has now been completed by 18 modeling groups from around the world. Danabasoglu, Yeager, and collaborators have analyzed the AMOC and related North Atlantic fields in the suite of models participating in this inter-comparison. Nontrivial differences in AMOC mean and variability are attributed to differences in the subgrid scale parameterizations, parameter choices, grid resolutions, and sea ice models used, but the comparison shows no obvious grouping of simulations based on model lineage, vertical coordinate, or salinity restoring (Danabasoglu et al. 2014).

Analysis of these simulations is ongoing, but preliminary results indicate that almost all participating models show an upward trend in AMOC strength over the last four decades of the 20th century, which is strongly related to enhanced deep convection in the Labrador Sea.

Considerable progress has been made in the past year in understanding the mechanisms of historical AMOC variability as simulated in the NCAR CORE-II simulation. Yeager and Danabasoglu (2014) separated the effects of time-varying momentum and buoyancy forcing and were thus able to pinpoint the origin of the late 20th century upward trend in AMOC seen in most CORE-II reconstructions. They show that it is related to increased Labrador Sea turbulent buoyancy forcing associated with the observed trend towards colder, drier wintertime atmospheric surface conditions in the deep-water formation region. Their results suggest a strong link between Labrador Sea SSH variability and buoyancy-forced, decadal AMOC variability with clear implications for AMOC monitoring and prediction.

The extent to which AMOC mean and variability are related to atmospheric internal variability has been explored using coupled interactive ensemble simulations, atmospheric and oceanic reanalyses, and forced ocean—sea ice hindcast simulations by Chang, Li, Kirtman, and colleagues. They have found that atmospheric internal variability contributes significantly to AMOC strength and variability in the Community Climate System Model version 3 (CCSM3; Wan et al. 2013). A recently defended Ph.D. dissertation by W. Kim links 20th century trends in the North Atlantic storm track with recent AMOC variability through the effects of high frequency atmospheric forcing on ocean mixing and deep water formation. Other recent results include the finding that model representation of the storm track is significantly impacted by the existence of SST bias in the Gulf Stream extension region (Hsieh et al. 2013), and that cold air outbreaks contribute significantly to the net winter turbulent heat forcing in both the Kuroshio and Gulf Stream extension regions (Ma et al. 2013).

Chang, Yeager, and Danabasoglu have begun work on a new project aimed at improving our understanding of the discrepancies in the late 20th century AMOC trends simulated in CMIP5 coupled models (which tend to show AMOC weakening) and CORE-II ocean—sea ice models (which tend to show AMOC strengthening). Preliminary results focused on the coupled and uncoupled versions of the CCSM4 model highlight differences in Labrador Sea buoyancy forcing that are attributed to the missing trend in NAO forcing in the coupled model (Kim and Chang 2013).

Decadal climate prediction – predicated largely on decadal AMOC variability – continues to be a topic of intense research. A major recent thrust has been the analysis of coupled model ensembles initialized from observed climate states following the protocols of the CMIP5 (Meehl et al. 2013). At NCAR, two different initialization approaches have been tested: the first utilizes historical ocean and sea ice states obtained from the CORE-II simulation and the second makes use of an ensemble adjustment Kalman filter (EaKF) ocean data assimilation system (Data Assimilation Research Testbed, DART) within the Community Earth System Model version 1 (CESM1; Karspeck et al. 2013). Both initialization approaches are found to outperform an autoregressive statistical model in predicting SST over broad regions of the Indian, western Pacific, Southern Ocean, and North Atlantic. The different initialization techniques showed varying benefits depending upon the region. When initialized skill is assessed relative to uninitialized simulations, which prescribe the same external forcings, only the North Atlantic stands out as a region of significant prediction skill on decadal time scales (Yeager et al. 2012; Karspeck et al. 2014).

Similarly, initialized decadal prediction experiments based on an ensemble coupled data assimilation (ECDA) were carried out at GFDL by Msadek, Delworth, Rosati, and colleagues. The system was found to have good skill in predicting the observed mid-1990s subpolar gyre weakening and warming when initialized after several years of persistent positive NAO (Msadek et al. 2014). In agreement with predictions based on other models by Yeager et al. (2012) and Robson et al. (2014), the warming was found to result from an increased overturning heat transport at midlatitudes. However, unlike in other models, Msadek et al. (2014) linked the predicted warming to changes in the barotropic circulation with an enhanced North Atlantic Current and a contraction of the subpolar gyre as warmer water was advected northward from the subtropics, consistent with previous work by Hatun et al. (2005).

Branstator, Teng, Meehl, and Gritsun have performed an analysis which compares intrinsic AMOC predictability with North Atlantic heat content predictability in a number of CMIP5 models. They find that the limit of AMOC predictability varies from model to model (from 4 to 20 years), and that 500 m heat content is in almost all cases more predictable than AMOC (Branstator and Teng 2014). However, time averaging changes this result, so that 5- and 10-year average AMOC is more predictable than heat content. An intriguing new result is the identification of certain AMOC and heat content patterns that are much more predictable than typical patterns, increasing the viable forecast range by up to a factor of five.

The differences in AMOC variability characteristics across a set of CMIP5 pre-industrial control simulations have been clarified using a frequency-dependent transfer function analysis by MacMartin et al. (2013). Tziperman, MacMartin, and Zanna have been examining frequency-domain relationships to understand the differences in AMOC variability simulated by the GFDL CM2.1 and CCSM4 models. They find little support for the hypothesis that the differences in AMOC variability are attributable to differences in Labrador Sea stratification, but a mechanism involving the westward propagation of subsurface Rossby waves may be playing a role.

McCreary, Timmerman, Furue, and Schloesser have extended their investigations of the dynamics of AMOC at high latitudes using an idealized model to isolate distinct mechanisms associated with buoyancy and zonal wind stress forcing (Schloesser et al. 2013). They have also begun to evaluate the effects of an eastern-boundary continental shelf in their simple 2-layer model and find that it impacts AMOC by inhibiting the offshore propagation of Rossby waves (Furue et al. 2013).

Denmark Strait Overflow Water (DSOW) is a key constituent of the NADW, which supplies the return flow of the AMOC. Pickart, Spall, and colleagues have synthesized a variety of observations in the vicinity of Denmark Strait and Fram Strait to study the path and transport of the newly discovered North

Icelandic Jet (NIJ), which merges with the East Greenland Current (EGC) to provide the source waters for the DSOW (Vage et al. 2013). The analysis of observations from this region is complemented by high resolution modeling work, which has shed light on the dynamics of the NIJ and the separated branch of the EGC. Yang and colleagues have also done recent work on the dynamics of the EGC and NIJ, using a numerical model to separate the effects of wind and buoyancy forcing on DSOW (Yang and Pratt 2013). In a recently published paper, they argue that the Nordic Seas have a limited buffering capacity to prevent AMOC shutdown because the main reservoir of dense water north of the sill is not available to the overflow currents (Yang and Pratt 2013).

Spall has also developed an idealized numerical model of the Arctic Ocean, which compares well with an eddy-resolving model in terms of Arctic halocline depth, freshwater content, and surface salinity under steady forcing. This simple model will be used to explore the Arctic response to transient atmospheric forcing; a similar conceptual model approach will be used to explore the forced dynamics of a convective basin, in collaboration with Yasuda.

Cessi and Wolfe have used a simple, semi-enclosed basin model to examine the freshwater feedbacks, which control the residual overturning circulation (ROC) between the North Atlantic and Southern Ocean in the adiabatic limit. In this regime, the inter-hemispheric flow is restricted to isopycnals, which outcrop at both endpoints. They have recently shown that freshwater forcing increases the range of shared surface isopycnals beyond that obtained with thermal forcing alone, thereby enhancing the ROC. Furthermore, freshwater feedbacks give rise to multiple AMOC equilibria in their model, with multi-decadal oscillations observed in the transition to the AMOC "off" state (Cessi and Wolfe 2013).

The role of the Southern Ocean is also highlighted in the recent work of Fedorov and Sevellec, who found deep ocean perturbations (specifically in the Southern Ocean) are most effective at reducing upper ocean model bias on decadal timescales (Sevellec and Fedorov 2013). This has important ramifications for decadal prediction suggesting that initialization errors in the deep Southern Ocean may be a limiting factor in predictability (Sevellec and Fedorov 2014).

Dong, Goni, Baringer, and Halliwell have used both observations and climate models to investigate the strength and variability of AMOC and MHT in the South Atlantic. CMIP5 models do not simulate the seasonal cycle of AMOC at this latitude correctly because they tend to overestimate the Ekman component, whereas the geostrophic component dominates the seasonal cycle in observations. This finding is similar to that reported in Msadek et al. (2013) concerning the simulated AMOC and MHT at 26°N.

Several projects are focused on clarifying the impacts of freshwater forcing on AMOC variability. Condron and Bradley developed a thermodynamic iceberg model (MITberg), which gives realistic iceberg trajectories and melt rates when coupled to the MITgcm (at 1/6° resolution). They have recently designed a suite of experiments to test the impacts of increased Greenland iceberg calving rates on AMOC and subpolar gyre circulation. Deshayes, Curry, and Msadek have investigated the relationship between salinity and the subpolar gyre circulation, both in terms of gyre strength and AMOC, in five coupled climate models (Deshayes et al. 2014). A principal result of the paper was a broadly inconsistent representation of freshwater budgets and circulation in the subpolar North Atlantic in the CMIP5 climate models. However, all models showed that the subpolar gyre freshwater content changes vary out-of-phase with the AMOC at multi-decadal frequencies, i.e., the subpolar gyre is saltier when the AMOC is more intense and the changes in salinity lead the AMOC in some models like the GFDL CM3. Furthermore, Deshayes et al. (2014) suggested that the driving role of salinity on the circulation depends on frequency – with a salty subpolar gyre corresponding to a weaker circulation on inter-annual timescales and the opposite relationship on longer timescales.

In previous years, Weijer and collaborators investigated the impacts on AMOC of anomalous freshwater discharge from Greenland in both eddy resolving and non-resolving model simulations. Their more recent work looks at the response of the AMOC to anomalous salt import from the South Atlantic associated with temporal variations in Agulhas leakage. They performed a coherence analysis of a 500-year CCSM4 control simulation and found no causal impact of Agulhas leakage salt import on AMOC (Weijer and van Sebille 2013). However, this result is inconclusive because the coarse resolution model overestimates the mean volume exchange between the South Indian and Atlantic Oceans (Weijer et al. 2012) and therefore severely underestimates the salinity variability in the region west of the Agulhas retroflection.

Wang and colleagues have performed diagnostic and modeling studies which appear to confirm the hypothesis that the Atlantic Warm Pool (AWP) is responsible for a negative feedback on AMOC variations through its controlling influence on the surface freshwater budget of the tropical North Atlantic (Zhang et al. 2013; Wang and Zhang 2013; Wang et al. 2013). They also identify common patterns of global SST bias associated with AMOC in CMIP5 models, which underscore the importance of inter-hemispheric teleconnections related to Atlantic overturning.

Zhang and collaborators completed a study which closely scrutinized the role of aerosol forcing in the Atlantic Multidecadal Variability (AMV) simulated by the Hadley Centre Global Environmental Model, version 2, Earth system configuration (HadGEM2-ES). In contrast to Booth et al. (2012), whose analysis of the HadGEM2-ES 20th century simulation led them to conclude that aerosol forcing is a primary driver of the observed AMV, Zhang et al. (2013) suggest that the model simulates excessively strong aerosol effects. They show that there are significant discrepancies between observed and simulated upper-ocean heat content, Atlantic SST anomaly patterns, and subpolar Atlantic salinity, which call into question the fidelity of the simulation and cast doubt on the claim that aerosols are more important than AMOC in driving AMV.

2.4 Climate Sensitivity to AMOC: Climate/Ecosystem Impacts

Many of the projects presently aligned with Task Team 4 are closely linked to other US AMOC objectives such as understanding AMOC mechanisms, fingerprinting, and its future state. These studies are broadly organized around topics related to the impacts of AMOC variability, for example on the ice sheets, extreme weather events, and sea level rise.

- "Studying the modulation of extremes in the Atlantic region by modes of climate variability using a coupled regional climate model," led by Saravanan and Chang, is assessing the effects of fine spatial resolution and air-sea coupling on regional extreme weather and climate events in a coupled regional climate model (CRCM).
- "Mechanisms and Predictability of the Global Climate Impacts of Atlantic Multidecadal Variability," led by Ting, Kushnir, and Camargo, is developing ways to separate the impacts of natural AMV on North American climate from the consequences of anthropogenic forcing.
- "The Contributions of Ocean Circulation to North Atlantic SST," led by Kelly and Dickinson, is investigating the relative importance of air-sea fluxes and ocean circulation to generating inter-annual SST anomalies in the North Atlantic Ocean in the context of large-scale SST patterns such as the AMV.

- "Influence of the continental ice retreat on future global climate," led by Hu, is studying potential impacts of the continental ice retreat, including the melt of glaciers and mountain ice caps, and the Greenland and Western Antarctic Ice Sheets, on the future global climate with focus on AMOC.
- "Uncertainty in future regional sea level rise due to internal climate variability," led by Hu, is investigating the impact of atmospheric and oceanic internal climate variability on projected regional and global mean sea level rise in a global warming scenario.
- "Glacier-Ocean Coupling in a Large East Greenland Fjord," led by Straneo, Hamilton, Stearns, and Sutherland, is investigating ice sheet ocean interactions in a southeast Greenland fjord to identify links between large-scale changes in the North Atlantic ocean-atmosphere system and dynamic changes of the Greenland Ice Sheet.
- "Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt," led by Gille and Martinson, is characterizing meridional heat transports for multiple regions in the Antarctic - South Pacific sector.
- "An Interactive Multi-model for Consensus on Climate Change," led by Duane, Tsonis, Kocarev, and Tribbia, is testing the hypothesis that synchronization of climate modes may provide opportunities for distinguishing between climate variability and climate change in coupled models.

One of the important issues in AMOC research is the potential for North Atlantic SST anomalies to influence precipitation extremes, such as droughts and floods, over continental regions. Using a high-resolution coupled regional climate model, Saravanan and Chang investigated whether long-term precipitation trends over North America could be attributed to regional modes of SST variability. Their results suggest that North Atlantic SST strongly controls Midwest decadal drought and pluvial periods, but that it plays a minimal or secondary role in modulating extreme flood events on shorter timescales of weeks to months (Patricola et al. 2013). Specific case studies yielded mixed results implying that extreme hydrological events can either be enhanced or insensitive to ocean-atmosphere interactions, but also depend on other factors.

Ting and collaborators have also been investigating SST variability associated with AMV and AMOC variability in order to assess linkages to global hydroclimate and North Atlantic hurricane activity (Ting et al. 2009, 2011). More recently, Ting et al. (2013) examined the representation of these impacts in CMIP5 models comparing the phenomenon in pre-industrial runs, historical runs, and future projections. In the latter two cases, they separated the impact of greenhouse gas warming from natural variability. The results were essentially consistent with a previous study using CMIP3 models. As a group, the coupled models used for the IPCC assessments are capable of simulating the spatial structure of the AMV phenomenon as well as its seasonal impacts – with a caveat that they generally exhibit a weaker footprint in the tropical Atlantic compared to observations. The models however diverge widely in their representation of time scales of AMV, leading to broad difference in their depictions of AMOC variability.

Low frequency, basin-scale patterns of SST associated with the AMV are governed by the relative roles of air-sea fluxes and the ocean transport of heat (horizontal advection, diffusion, and vertical temperature structure). The terms of the latter are exceptionally difficult to estimate directly from observations. Instead, Kelly and Dickinson have estimated the ocean transport terms as a residual of ocean heat content anomalies (derived from altimetric SSH anomalies) minus the air-sea fluxes (derived from observations and reanalysis products). With this method, they constructed time series of heat content budgets in the three regions representing the tripole pattern of the AMV and found that in each region heat transport anomalies played a larger role than surface heat flux anomalies (Kelly et al. 2014). By focusing on long time scales related to the AMV, the ocean circulation influences are inferred to reflect AMOC variability. Their analysis suggests that the dominant contribution to the AMV is anomalous ocean circulation, rather than air-sea heat fluxes.

Sea level rise is expected to both contribute to and be influenced by AMOC variability. Two studies employing output from a coupled global climate model (GCM) examined separate aspects of regional sea level rise and global climate. Hu and Deser (2013) used a large ensemble of CCSM3 integrations forced with increased greenhouse gas concentrations to assess uncertainties in 21st century sea level rise associated with internal climate variability. They concluded that simulated regional sea level rise at mid-century can regionally vary by a factor of two, with the North Atlantic and Pacific exhibiting the greatest ranges. This uncertainty results primarily from internal variations in the wind-driven and buoyancy-driven ocean circulations. AMOC significantly determines the regional Atlantic sea level rise pattern and could also impact sea level rise in the Pacific.

The second study evaluated potential impacts of continental ice sheet retreat on global sea level and AMOC. It found that over the next two centuries AMOC strength is sensitive only to injection of melt water into the North Atlantic, while loss of water from the Antarctic Ice Sheet has little, if any, impact (Hu et al. 2013). When runoff from land-based ice melt becomes large enough to generate a net freshwater gain, the AMOC weakens, but does not cool the global climate. Instead, the weakened AMOC slows the warming at high northern latitudes, particularly in Europe.

Elements of the AMOC play a potentially important role in the observed speedup of Greenlands's marine-terminating outlet glaciers, notably through changes in the subpolar gyre circulation and an associated increased penetration of warm Atlantic waters into Greenland's fjords (Straneo et al. 2013). Straneo and Heimbach (2013) found that, at present, the North Atlantic Ocean and atmosphere are the warmest on the historical record, even warmer than the previous warmest phase in the 1930s. This warming coincides with evidence of dynamic ice loss from Greenland and raises questions about the role of AMOC and poleward heat transport changes in driving ice loss from the Greenland Ice Sheet. Observations within the fjord have revealed that during winter the fjord circulation and properties – and thus the submarine melt rate – is largely controlled by passing synoptic wind-events which drive rapid fjord-shelf exchange and can flush the fjord within days (Jackson et al. 2014). This means that variability on the shelf is rapidly communicated to the glacier margins.

In the Southern Ocean, meridional overturning in the Pacific is analogous to meridional overturning in the Atlantic. Mechanisms of ocean overturning circulation and meridional heat transport along West Antarctica, where ice sheet melting is the largest, have been studied as an analog to similar melting and ocean overturning in the Atlantic sector of Antarctica or the North Atlantic (Gilroy et al. 2013; Zilberman et al. 2013; Zilberman et al. 2014). Using a combination of data from Argo floats, altimetry, and reanalysis products, they find that meridional heat transport in the study region is correlated with the strength of the SAM, but not with ENSO. 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 the Amundsen Sea Embayment. Gilroy et al. (2013) found that air-sea fluxes dominate the heat budget above the pycnocline, but do not appear to influence the denser water that is expected to contribute to basal melting. Rather, heat is advected into the eastern end of the embayment as a consequence of wind-stress-curl.

Theoretical aspects of climate variability mode synchronization are being explored to potentially distinguish between climate variability and climate change. Tsonis and colleagues have identified instances during the 20th century when modes of climate variability synchronize and lead to a change in climate that has been referred to as a climate shift. For example, they identify such a shift in the early 1940s.

3 NEAR-TERM RESEARCH PRIORITIES

The near-term research priorities, articulated below, are largely based on the discussions that occurred during the 2012 annual US AMOC Science Team meeting. However, they are updated here to reflect the outcomes of recent Task Team teleconferences. Near-term priorities will be thoroughly revisited and revised, if needed, and long-term goals will be discussed at the upcoming annual meeting in Seattle (September 2014). A discussion of progress towards accomplishing priorities and plans for continued work are also included below.

3.1 Observing System Implementation and Evaluation

Near-term priorities

- Improve understanding of the meridional coherence (and/or lack thereof) of the AMOC and the mechanisms that control AMOC changes. Augmented elements of an Atlantic-wide monitoring system (OSNAP to be implemented and enhancements to SAM to be proposed), as well as dynamically consistent model-data synthesis methods to combine the heterogeneous observational pieces (including satellite data), will play an important role.
- Expand the existing observing system to better capture the deep ocean and quantify the role of deep temperature and salinity signals in controlling AMOC variability continues to be a priority. Enhancements such as 'deep Argo', full-depth gliders, and enhanced moored observations should be evaluated in the context of a full-depth observing system.

Improving understanding of the meridional coherence of AMOC, and the mechanisms that control AMOC changes, is and will continue to be one of the key areas of research. The RAPID-MOCHA-WBTS array at 26°N is the only truly trans-basin array providing data at present, but other programs are providing crucial observations of key components of AMOC at other latitudes (e.g., Line W, SAM array, MOVE array, Norröna, Oleander and Davis Straits sections, the altimeter+Argo estimates at 41°N). Additional data for studying AMOC meridional coherence will soon be available now that the new OSNAP is funded and scheduled for deployment in mid-2014 along with several new international contributions having been deployed in late 2013 augmenting the SAM pilot array at 34.5°S as part of SAMOC. Some of the highest priorities are seeing the OSNAP deployment happen and continuing to augment the existing SAMOC array, as required, to complete the 34.5°S trans-basin array.

Ongoing research using prognostic models will continue to provide many important insights in this area (e.g., Danabasoglu et al. 2014). Attention should also remain on the value of available satellite data, especially altimetry, for deciphering ocean circulation variability in the Atlantic (e.g., Hakkinen et al. 2013). Formal model-data synthesis provides a baseline for the use of the existing global observing system consisting of full suite of satellite data (altimetry, scatterometry, gravimetry, and microwave radiometry-derived SST), in conjunction with in situ data (CTD, XBT, and Argo), to produce basin-wide (and global) ocean state estimates with closed budgets of heat and freshwater (Wunsch and Heimbach 2013b).

A near-term goal will be to incorporate the complete set of mooring arrays listed above into these estimates to assess and/or improve their skill. Finding innovative ways to utilize data from multiple latitudes to address the thorny questions of AMOC dynamics continues to be a key goal.

Expanding the existing observing system to better capture the deep ocean and quantifying the role of deep temperature and salinity signals in controlling AMOC variability continues to be a priority. The existing global ocean observing system captures only the upper 2000 m of the ocean aside from a few specific locations (e.g., the RAPID-MOCHA-WBTS array), and as such does not measure the entire deep lower limb of the AMOC. Enhancements such as 'deep Argo', full-depth gliders, and enhanced moored observations in the deep ocean must be evaluated in order to aid in the future design of a more comprehensive deep ocean observing system. Furthermore, new technologies and/or new business models for collecting observations (e.g., the proposed Oceanscope program) should be considered in terms of their ability to aid in AMOC studies.

3.2 AMOC State, Variability, and Change

Near-term priorities

- Continue 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.
- Develop a set of metrics for the AMOC, such as AMOC both in depth and density space and in temperature-salinity space, and including water mass transformation.
- Understand the relationships between surface heat and freshwater fluxes and the set of AMOC metrics and establish connections to climate signals such as the NAO.
- Focus assimilation and hindcast modeling efforts on reaching a consensus on the variability of the AMOC over the past few decades throughout the Atlantic basin, and on placing realistic uncertainty bounds on these estimates. It is important to understand the uncertainties of existing estimates and the accuracies required to detect climatically important AMOC-related changes. Encourage use of data assimilation products as well as comparisons between coupled high-resolution and low-resolution models to understand AMOC variability.
- Investigate MHT attributed to AMOC, as it provides the main connection to the climate system. 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.
- Identify if there is a connection between AMOC and the recent hiatus in global warming and deep ocean heat uptake and, if so, investigate controlling mechanisms.
- Understand the interaction of AMOC with variability in North Atlantic subpolar region and coordinate analyses with OSNAP efforts. Describe and understand mechanisms of any signatures of meridional coherence of AMOC (especially between subpolar and subtropical regions) from both model and observational analyses.
- Understand the linkage between the subpolar North Atlantic with accelerating changes in the Arctic including changes in sea ice extent and heat and fresh water exchange between the Arctic and the North Atlantic.

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. In models, it is straightforward to derive the zonally integrated meridional stream function, and its maximum value or value at a specific latitude can be used as an index. 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 from observed quantities such as SST. The identification of such a fingerprint(s) will contribute to understanding of the impacts of AMOC variability on ecosystems, carbon cycles, and global climate.

A recommended first approach 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. This work suggests that the dipole pattern in the altimeter SSH 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 (e.g., 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 times 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 US AMOC annual meeting, and invited two paleoclimate experts (Saenger and 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, Horton reviewed the extensive, currently available proxies for sea level on the US East Coast, such as those obtained from salt marshes that could provide several thousand years records with decimeter vertical accuracy and decadal temporal accuracy. These records could be used to determine whether they could be adequate AMOC proxies.

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 (e.g., meridional volume and heat transports at all latitudes and all time scales) by making simultaneous use of the complete historical observational dataset within the framework of a model.

Numerous estimates of overturning variability are available from ocean state estimates. However, different groups use a variety of approaches for assimilation, 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 inter-compare 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 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 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 datasets 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. Msadek et al. (2013) has produced significant work towards advancing this near-term priority in the past several years by 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 26.5°N.

The understanding of the AMOC and MHT relationships will also help identify 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. For example, Garazoli et al. (2012) shows that the South Atlantic is responsible for a northward MHT with a mean value of 0.54 ± 0.14 PW. Statistical analysis suggests that an increase of 1 Sv in the MOC leads to an increase of the MHT of 0.04 ± 0.02 PW. 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.

Developing a set of metrics for the AMOC

A set of metrics for the AMOC, such as AMOC in depth and density space, in temperature- salinity plane, and including water mass transformation, would be very useful for evaluation of AMOC in climate models. In climate models, the AMOC is often estimated in depth space, which shows a maximum south of the subpolar region. However, in density space the maximum AMOC is shifted to the subpolar region (Zhang 2010), similar to estimates in density space using the observed hydrographic data (Talley et al. 2003). In depth space north of 45°N, the northward and southward transports compensate each other within the same depth layer, disguising the maximum AMOC near NADW formation sites, thus resulting in a maximum at lower latitudes. Hence the typical estimation of AMOC in depth space is not suitable at mid and high latitudes (Zhang 2010). This suggests that for studies of subpolar AMOC variations and their meridional connectivity with those in the subtropics, AMOC variations need to be estimated in density space instead of depth space. Moreover at mid- and high-latitudes, if the AMOC is estimated in temperature-salinity plane, the information of water mass transformation can be studied directly. This approach provides additional insights to distangle the relationships between AMOC and surface heat and freshwater fluxes, and water mass transformation, as well as to understand the connections to climate signals such as the NAO.

Connection between AMOC and the recent hiatus in global warming

The observed global mean temperature shows an almost zero short-term trend at the beginning of the 21st century. This pause is often called a "hiatus" in global warming. Various studies (Kosaka and Xie 2013; Meehl et al. 2013) suggest that the hiatus in global warming is mainly caused by internal variability. England et al. (2014) suggest that changes in the tropical Pacific driven by changes in the trade winds can explain much of the hiatus. At the same time, the global deep ocean heat content continued to increase during the hiatus period, suggesting the ocean heat uptake has played an important role in the hiatus in global surface temperature. Further investigations are needed to understand the linkage between deep ocean heat uptake and the AMOC and whether there is a role for the North Atlantic in controlling surface warming on decadal times scales.

Meridional coherence of AMOC

An open question is whether there is a significant connection in AMOC between the subtropical and subpolar regions. Both modeling and observational studies are key to making progress on this question. The OSNAP program is an important step towards understanding the connection between subpolar regions of AMOC with that observed at the latitude of the RAPID array at 26°N. Bingham et al. (2007) found a low correlation at zero time lag of AMOC in depth space in climate models and interpreted the results as a low meridional coherence between subpolar and subtropical AMOC variations. However, Zhang (2010) showed that in density space the low frequency variations of AMOC at high latitudes are significantly connected with those at low latitudes but with a several year time lead, although the correlation is low at zero time lag, using GFDL CM2.1 control simulations. The several-year time lead is due to the slow advective time scale for the propagation of a significant part of the low frequency variations of AMOC along interior pathways. This is contrary to the traditional view of the propagation of AMOC variations only along western boundaries.

Studies focusing on understanding the structure and causes of the variability of AMOC in both the subtropical and subpolar regions, along with coordinated analyses with OSNAP efforts, should be encouraged.

Linkage between the subpolar North Atlantic and Arctic

Satellite observations reveal a record-breaking low September Arctic sea ice extent in 2012. Over the satellite period (1979-2012), September Arctic sea ice extent declined 49% compared to 1979 to 2000 climatology. The extreme low summer Arctic sea ice extent in 2012 continued the rapid downward trend seen in the early 21st century. The observed decline has been attributed in part to greenhouse gas forcing (Stroeve et al. 2007) and some climate models project that the Arctic Ocean will be ice-free in the summer within a few decades (Stroeve et al. 2012; Massonnet et al. 2012). Climate model studies have indicated a possible role for internal climate variability in the recent Arctic sea ice decline. There is some evidence from the GFDL model CM2.1 of a statistical link between the AMV-AMOC and Arctic sea ice extent, especially in winter (Mahajan et al. 2011). The changes in Arctic sea ice could also impact the size of the freshwater export from the Arctic to the North Atlantic through Fram Strait, with potential linkages to changes in AMOC. Additional studies are encouraged that will lead to improved understanding of the above linkages.

3.3 AMOC Mechanisms and Predictability

Near-term priorities

High priority will continue to be given to efforts directed toward understanding AMOC variability mechanisms, roles of atmospheric forcing and ocean–atmosphere feedbacks in this variability, and their model dependencies, using tools ranging from idealized theoretical models to the full general circulation models.

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

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. Little is known about the role of high latitude oceans (i.e., the Southern and Arctic Oceans) teleconnections in AMOC variability. In particular, the magnitude and impact of freshwater transports from the South Atlantic and Arctic remain to be quantified. There is also a need to better understand the role of overflows in controlling AMOC fluctuations, as model analyses do not show consistent results on this issue. Another emerging question is related to stability (or regime) of the AMOC and the role of freshwater forcing in this stability. For example, it is important to understand if the present AMOC regime is stable and if an increase in freshwater at high latitudes will affect this stability. Finally, as model resolution increases, it has become possible to address the question of the importance of mesoscale motions in simulating and understanding AMOC variability.

The biggest barrier towards answering all the above questions, particularly regarding mechanisms, is the lack of sufficient observational data to critically assess the realism of the model-based results. Therefore, new observations and synthesis of existing observations, including synthesis of proxy data, need to be developed to discriminate various model-based proposed mechanisms against the observational information. This effort should be carried out in close collaboration with the program objective to design and implement an AMOC monitoring system.

AMOC prediction and predictability

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 (WGOMD) and the Global Synthesis and Observational Panel.

Progress continues on AMOC predictability and decadal prediction research led by climate modeling centers in the US and around the world. The US AMOC program recognizes that there are related ongoing efforts regarding analysis of these simulations. The 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, North Atlantic 1960s cooling, and the sudden decrease in AMOC strength during 2009-2010. Such verification case studies should be coordinated using a standard set of metrics.

Two of the biggest issues continue to be proper initialization of decadal prediction simulations and bias correction of the solutions, 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 US modeling centers, continue to make decadal climate prediction a useful reality. It is also important to reduce model biases that affect the representation of the AMOC in order to improve the reliability of the decadal predictions that rely on the AMOC.

Action items

Two action items have been identified to address the outlined near-term priorities:

- 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 sub-grid scale physics (e.g., Nordic Sea overflows, meso- and submeso-scale parameterizations).

- Task Team 3 will provide common analysis frameworks both for modeling studies and relevant observational analysis, and will help 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 US CLIVAR AMOC website.

3.4 Climate Sensitivity to AMOC: Climate/Ecosystem Impacts

As one of its foundational objectives, the US AMOC Science Team targeted assessing the degree to which an evolving AMOC will itself influence climate variability. As stated in the 2007 Implementation Strategy, "the overall expectation for this new program is that it will dramatically improve our understanding of the links between AMOC variability and climate system impacts, especially those relating to sea ice, marine ecosystems, the ocean carbon budget and sequestration, and regional and global sea level." Over the first six years of the program, only incremental progress has been realized in many of these areas reflecting a rather limited set of projects specifically identified to address AMOC impacts within the program. A broader survey of projects, through agency and community contacts, is warranted to ascertain the scope of relevant research being conducted beyond the Science Team's purview. Furthermore, it is recognized that many of these topics may be best addressed through engagement of other research communities (e.g., cryosphere, biogeochemistry, and marine ecosystems) to scope shared science objectives and foster collaborative research activities. Such engagement has been undertaken primarily through invited presentations and focused sessions at US and international AMOC science meetings in 2012 and 2013. The external review report issued in 2013 stressed the value of connecting to other research communities to develop understanding of coupled climate dynamics, climate feedbacks, and climate impacts of critical importance to humans. The review recommended expanding beyond invited presentations at AMOC meetings and to develop broader interactions with these other communities through focus groups organized for AGU meetings.

In past reports, the near-term priorities for this program objective tended to bundle all "impacts" into a single priority statement. Given the distinct nature and variety of the communities with which US AMOC will engage to address these topics, separate and specific near-term priorities regarding AMOC impacts have now been identified.

Near-term priorities

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

Climate sensitivity to AMOC

Assessing AMOC's role in the global climate includes two principal foci: (i) quantifying the AMOC contributions to generating SST variability relative to other factors (e.g., surface heat fluxes, other ocean circulation components, and external forcing agents whether natural or anthropogenic); and (ii) understanding the degree to which AMOC-related SST variability affects the overlying atmosphere (e.g., extratropical storm tracks, hurricanes), and how the atmospheric response is communicated through teleconnections, potentially influencing remote climate variability and triggering extreme events over land (e.g., droughts and pluvials).

Progress has been made in quantifying how AMOC variability affects climate through its influence on basin-wide SST changes (AMV). Both modeling experiments and observations implicate anomalous ocean circulation, particularly AMOC, as the dominant contribution to the AMV. Whereas global coupled models largely agree on AMOC's role in orchestrating low-frequency variability of subpolar SST, they diverge on the extent to which it influences SST over the broader North Atlantic Basin. Questions remain regarding the relative importance of the radiative effect of atmospheric greenhouse gas concentrations and aerosols, as well as the timescales of AMV, on which climate models widely diverge. Research linking AMOC and AMV is intrinsically linked to studies of AMOC fingerprinting and mechanisms, the purview of Task Teams 2 and 3. As such, this near-term priority should be closely coordinated and summarized in collaboration with the other Task Teams.

Progress has also been made on focus (ii) regarding how the atmosphere responds to AMOC-generated SST changes, in the context of North Atlantic atmospheric baroclinicity (and its influence on tropical and extratropical storm activity) through controls on remote hydroclimate characteristics (a strong influence on decadal-scale droughts and floods, and minimal or secondary influence on short-term climate extremes). Several investigations were completed in 2013 leaving an open pathway for continued advances in this research priority, which would benefit from future investment.

Cryosphere sensitivity to AMOC

AMOC variability is expected to influence high-latitude ice sheets and sea ice directly through changes in ocean heat transport, and indirectly through changes in atmospheric forcing and storm tracks. Rates of melting, advection of sea ice and density anomalies, and consequent changes in buoyancy fluxes can in turn influence AMOC, particularly in the deep mixing regions where the upper limb of the AMOC feeds its lower limb. Studies of such feedbacks are included in Task Team 3 efforts to understand AMOC mechanisms and changes.

A US CLIVAR-sponsored international workshop convened in June 2013 to discuss the problems of "Understanding the Response of Greenland's Marine-Terminating Glaciers to Oceanic and Atmospheric Forcing" and the challenges for enhancing observations, process understanding, and modeling. Workshop attendees produced a six-component framework to advance scientific understanding on this topic, which is detailed in the workshop report (Heimbach et al. 2014; available at http://www.usclivar.org/meetings/griso-workshop. Among these, the most relevant to US AMOC efforts is the development of a Greenland Ice-Ocean Observing System including long-term in situ time series of critical glaciological, oceanographic, and atmospheric variables at key locations. Combined with existing remote sensing and other observational networks, this observing system would significantly address the AMOC-cryosphere near-term priority.

Representatives from the Arctic sea ice community are presently missing from Task Team 4, and should be engaged to inform and advise the US AMOC Science Team.

Impacts of AMOC variability on global and regional sea level

AMOC changes are expected to affect global mean sea level through influences on mass input (e.g. Greenland ice sheet melt) and net oceanic heat uptake (and consequent thermal expansion). AMOC changes can additionally influence sea level regionally through dynamic wave adjustment processes. New studies initiated in late 2013 are analyzing observations and model simulations to assess the contribution of AMOC to regional sea level changes in the Atlantic basin.

Impacts of AMOC variability on carbon and biogeochemical cycles

The impacts of AMOC on carbon cycles were discussed in a mini-workshop at the 2012 US AMOC PI meeting, and specific recommendations developed by Task Team 4 were set forth in last year's progress report.

- Organize one or more workshops bringing the physical and biogeochemical communities together to address fundamental carbon processes (e.g., the seasonal cycle) in the North Atlantic;
- Enhance the carbon observation network in the North Atlantic, including biogeochemical Argo floats and in situ biogeochemical observations; and
- Improve model simulations by 1) organizing a coordinated CORE-type ocean model intercomparison study focused on carbon cycle simulation in the North Atlantic, 2) working together with the CMIP5 community on diagnosing and understanding carbon cycle processes within the CMIP5 model ensemble, and 3) collaborating with the ocean data assimilation community toward ocean carbon data assimilation.

An opportunity to address these recommendations is provided by a spring 2014 international workshop, organized by the Ocean Carbon Biogeochemistry Program (with participation of US AMOC) and sponsored by NSF and EU Horizon 2020. Spurred by the Galway Agreement of 2013, which launched a EU/Canada/US alliance to promote " a healthy and well-understood Atlantic Ocean" for the "well-being, prosperity and security of present and future generations," the workshop is convening researchers across multiple disciplines (physical oceanography, marine biogeochemistry, biodiversity, ecosystem dynamics, paleoceanography, and resource management) from North America and Europe to inform the planning of a major international research initiative. The cooperative effort is intended to increase knowledge of key components of the North Atlantic-Arctic physical and biogeochemical system (e.g., AMOC, spring bloom timing, biological carbon pump, ecosystem structure) including the dynamics of these processes and mechanistic links to circulation and climate change. Several Science Team members are participating and it is anticipated that this initiative will provide avenues to broaden US AMOC engagement with the biogeochemical and ecosystem research communities.

Action Items

Two action items have been identified to address the near-term priorities:

- Task Team 4 will recruit new PIs working on carbon cycle in the Atlantic by directly reaching out to other groups (e.g., OCB) and by surveying an expanded list of agency funded projects.
- Task Team 4 will strengthen US AMOC coordination with other national and international science communities (particularly the International CLIVAR Atlantic Panel) to address AMOC impacts on the cryosphere, sea level, carbon/biogeochemistry, and marine ecosystems. Specifically, the team will continue engagement of the Greenland Ice Sheet-Ocean Interactions community; develop communication and collaboration with the sea ice science community; survey opportunities for engaging activities on sea level change, particularly the evolving WCRP grand challenge on regional sea level; and follow-up on recommendations from the 2012 action items for carbon cycle science community engagement. Participation of US AMOC scientists in the spring 2014 workshop on the North Atlantic-Arctic provides an opportunity to establish connections on several of these topics.

4 RELATED ACTIVITIES TO SUSTAIN

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

4.1 Large-scale Observations

The research projects that are addressed under the Task Team 1 component of the US AMOC program, coupled with other existing large-scale sustained observing systems (e.g., Argo, satellite measurements, repeated hydrographic ship sections, surface drifters, etc.) and synthesis efforts to combine the heterogeneous data streams into a coherent dynamical framework, are crucial for the analysis of data and models for improving understanding of the AMOC and the large-scale climate system. The general requirements for sustained large-scale observations and synthesis were described in detail in the 2010 US AMOC Science Team report and are not repeated here for brevity. They have remained, and will remain for the foreseeable future, the same. In fact, recent research continues to suggest an urgent need to maintain global-scale continuous observing systems in order to understand climate variability on decadal and longer time scales, including the AMOC observing projects that are underway and/or are getting started in 2014. These programs are based on the detailed requirements for the sustained ocean observing system that were established at the OceanObs'09 Conference (http://oceanobs09.net). The responsibility for the design and implementation of these observing systems lies with NASA, NOAA, and NSF and the many international partner agencies around the world, and will require resources above and beyond those that can be explicitly provided by the US AMOC program to be successful.

4.2 Proxy Records and Analysis

Decades of paleo research have shown a clear link between cold harsh epochs and reduced AMOC on orbital to centennial time scales. An assessment of whether this relationship exists on interdecadal time scales is of central importance to the US 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 multi-decadal and centennial scales:

- 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 changes on decades to centuries. This is in contrast with hundreds to thousands of sites on land around the North Atlantic basin.
- The temporal resolution of paleoclimate data needs to be improved. To resolve decadal changes requires sampling at the centimeter scale (very expensive) and dating very closely.

- Sufficient, well-resolved sites are needed to determine if the observed paleo changes reflect truly low frequency variability on multi-decadal and centennial scales.
- Multiproxy studies are needed. No single paleo proxy measurement is sufficient to recreate ocean circulation changes. Combinations of measurements on the same samples are required for robustness.
- 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 on decades to centuries. Analyses of AMOC state and variability should explore the relationship between potential paleo proxies and AMOC state using both paleo observations and climate model simulations. High-resolution 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 suggest that the subsurface temperature in this region could be used as an AMOC proxy.
- 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 we understand how sea level signals are related to the AMOC. Further development of such records as well as their interpretation should continue to be supported.
- The IPCC Fifth Assessment Report (AR5), Working Group 1, includes a chapter (Chapter 5: Information from Paleoclimate Archives) on paleo proxy, and the information from this chapter could be very useful to AMOC related research.

4.3 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 2 and the individual project reports in Appendix D. 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 section 2 indicate a need for eddy-resolving resolution in the ocean models to properly simulate many processes crucial to AMOC. Modeling activities require:

- The design and support of coordinated experiments to test the AMOC response to specific forcing (e.g., NAO, Southern Ocean winds). The large model-dependence of the AMOC mechanisms makes it difficult to identify how future atmospheric changes and internal variability may impact the AMOC. Such experiments will help in the assessment of a robust response. The use of different oceanic and atmospheric resolutions is encouraged to determine the importance of mesoscale eddies and storm tracks in shaping the AMOC response to climate perturbations.

- The design and support of coordinated decadal prediction experiments on AMOC-related climate events. This is important given the differences identified in the decadal prediction results that highlighted a key role for the AMOC (e.g., in terms of adjustment time, number of years ahead a prediction can be made, link between salinity initial conditions and AMOC).
- Sustained support for both the high-end coupled modeling activities at the large US national laboratories, including NCAR and GFDL, and high-end computers. 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 predictions of the AMOC remains a high priority.
- 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.
- 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.
- Sustained infrastructure that makes climate model output easily available over the web. Model outputs from the IPCC AR5 include prediction experiments with strong AMOC relevance. It is vital that scientists studying AMOC variability and predictability have open access to such model datasets from state-of-the-art coupled models.
- 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 analyses of these model data are 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.
- Sustained support to improve ocean data assimilation systems used to estimate the AMOC state in the past few decades. There remain substantial differences in the estimated variability of AMOC state derived from the current generations of assimilation products, especially on decadal time scales. While the lack of direct observations for the past decades contributes to these differences, limitations in understanding model and data errors (which dictate the outcome of the assimilation) are also important. Continuing efforts to improve the representation of the model and data errors of these systems can lead to better consistency and fidelity of the resulting estimation products, which would greatly enhance the potential of using these products to study the mechanisms of AMOC variability. Studies that demonstrate the relative impacts of existing observations in constraining the estimated AMOC state should continue to be encouraged and augmented.

- 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 ongoing efforts for coupled ocean-atmosphere data assimilation used to study the AMOC. Such efforts complement the projects funded under US AMOC for ocean model-based synthesis and observing system design studies. These efforts should be sustained and augmented in the future.

5 FUNDING

5.1 FY 2013 Agency Support

NASA, NOAA, NSF, and DOE, the federal agency sponsors of the US AMOC program in FY 2013, funded a total of 65 projects supporting the work of approximately 125 US scientists (see Appendix B). Of these projects, 16 were newly awarded in 2013. NASA provided $630K to support 7 projects exploiting satellite observations and datasets, and characterizing the attributes, variability, and mechanisms of the AMOC, with new projects focused on the South Atlantic MOC. NOAA allocated over $5.6M to a total of 21 projects to sustain in situ observations, document the state and variability of AMOC, and conduct multi-model analyses and experiments to better understand the mechanisms of AMOC variability and predictability. NSF provided between $7M to $8M in incremental funding to 26 projects to observe and document AMOC state and variability, improve understanding of AMOC mechanisms and predictability, and examine the links between AMOC and climate variability. DOE allocated $1.9M for 11 modeling studies examining the mechanisms of AMOC variability and predictability as well as the influence of AMOC on climate and sea level variability and change.

The four agencies, through their support of the US CLIVAR Project Office budget, cosponsored with the UK National Environmental Research Council RAPID-WATCH Program the second International US AMOC-UK RAPID Science Meeting held in Baltimore, Maryland, July 16-19, 2013.

5.2 FY 2014 Outlook

With the completion of 16 projects during 2013, there are 49 ongoing US AMOC projects supported by NASA, NOAA, NSF, and DOE at the start of FY 2014. NASA has solicited new projects in its ROSES-2014 research announcement for analysis and interpretation of the ocean circulation using satellite and in situ data. With a focused AMOC call for 2013 and the award of seven new projects, NOAA is not soliciting new projects for 2014. NSF will accept new AMOC project proposals through its standard solicitations for Physical Oceanography and Atmospheric and Geospace Sciences. DOE is accepting new project proposals in response to its 2014 funding opportunity to evaluate modeled natural climatic variability and human-caused climate change at global and regional scales.

The agencies are providing support to the US CLIVAR Project Office to organize the 2014 US AMOC Science Team Meeting scheduled for September 9-11, 2014 in Seattle, Washington.

6 SUMMARY

The US AMOC program, now in its sixth year, was developed as a US interagency program to increase understanding of AMOC. The purpose of the program is to bring together researchers studying AMOC, and build collaborations among modeling and observational communities to address problems related to AMOC variability, predictability, and climate impacts. The program currently includes over 50 funded projects. Annual program meetings, held either independently or jointly with the UK RAPID annual meetings, have been very successful in bringing together program PIs to share research results, develop collaborative projects, and identify research priorities and goals. In 2012, an external review committee reviewed the program. The review report finalized in June 2013 finds the program to be successful, impressive, and stimulating.

Research highlights and accomplishments of the program are reviewed within the body of this document. Updates to the near-term priorities that emerged from Task Team teleconferences are also included. The knowledge of AMOC variability and its linkages to climate variability is steadily advancing, but a thorough understanding of AMOC variability and its mechanisms still remains elusive. The summary below highlights a few of the accomplishments of the program in 2013 as well as some of the near-term goals:

1. NSF approved the proposal OSNAP, led by Lozier et al., in September 2013. OSNAP is designed to provide a continuous record of the full water column, trans-basin fluxes of heat, mass, and freshwater in the subpolar North Atlantic. It is planned for deployment in mid-2014, with an initial planned lifetime of four years. It consists of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West), and the second from the southeastern tip of Greenland to Scotland (OSNAP East). Studies looking into AMOC and North Atlantic subpolar gyre relationships should make use of the OSNAP data as they become available.
2. An emerging focus is on developing a trans-basin South Atlantic observing system with support from US and international partners. A core initial piece, the US AMOC SAM project has now collected more than four years of data, and it has been redeployed with batteries that will last through 2016. Initial results using 20 months of data suggest that the variability of the basin-wide MOC at 34.5°S is of comparable magnitude to that observed in the longer 26.5°N record.
3. Work towards establishing a full Atlantic-wide monitoring system continued in 2013 with the maintenance of various pieces in the South Atlantic (SAM), the subtropical Atlantic (mooring arrays at 16°N, 26.5°N, 39°N, and the Oleander section), the North Atlantic subpolar gyre, and the gateways to the Arctic (Davis Straits and Norröna Section). A focus this year was the derivation of associated heat and freshwater (or salinity) transports. Another ongoing effort is the development of synthesis frameworks to combine the diverse pieces of the observing system into a dynamically consistent Atlantic-wide state.
4. An improved understanding of the meridional coherence of the AMOC and the mechanisms that control AMOC changes will continue to be one of the key areas of research. Augmented elements of an Atlantic-wide monitoring system, as well as dynamically consistent model-data synthesis methods to combine the heterogeneous observational pieces (including satellite data) will play an important role.

Expanding the existing observing system to better capture the deep ocean and quantifying the role of deep temperature and salinity signals in controlling AMOC variability also continues to be a priority.

5. Various AMOC fingerprints have been identified and shown to be a useful tool for reconstructing past AMOC variations. It has been shown that AMOC variations at high latitudes lead AMOC fingerprints by several years, providing the physical understanding of why a stronger/weaker AMOC can lead to warming/cooling in the subpolar gyre by several years, and contribute to the enhanced decadal prediction skill in ocean temperatures in the subpolar gyre. The development of a multivariate fingerprint for AMOC, that would combine critical descriptors of the circulation and transport of ocean properties with those variables that are observed extensively or can be reconstructed from paleoclimate records, remains a high priority.
6. It is found that the typical estimation of AMOC in depth space is not suitable at mid- and high-latitudes. For studies of subpolar AMOC variations or their meridional connectivity with those in the subtropics, AMOC variations need to be estimated in density space, instead of depth space. AMOC variations estimated in density space reveal significant meridional coherence (especially between the subpolar and subtropical regions). Metrics for AMOC that include representation of AMOC in both depth and density spaces and water mass transformation should be established.
7. Using a variety of observations including altimetry as well as a variety of different models, a high degree of meridional coherence is found in meridional heat transport (MHT) from 30°S to 40°N, and the increased (decreased) MHT corresponds to increased (decreased) heat loss. Good agreement was found with the MHT estimates from the RAPID/MOCHA program. Efforts continued to estimate the mean and the variability in the MHT and MOC in the South Atlantic and their linkages to MOC and MHT in the North Atlantic. The relationships between modeled MOC intensity and MHT in various models are compared to observations. Such explorations of AMOC and MHT relationships in models in comparison with observation data should be encouraged.
8. The mechanisms and time scales of the AMOC remain largely model-dependent in both coupled and ocean—sea ice models. This has implications for the predictability limit of the AMOC and its associated climate impacts. Some mechanisms involving buoyancy forcing in the Labrador Sea or the westward propagation of subsurface Rossby waves appear to be key in driving AMOC variability, though their robustness across models remains to be shown. Particular priority should be given to efforts seeking to clarify the relative roles of heat/freshwater/momentum forcing, Nordic Seas overflows, Southern Ocean and Arctic Ocean teleconnections, coupled air-sea feedbacks, and mesoscale processes on AMOC variability and stability. A synthesis of existing observations should be developed, including synthesis of proxy data to discriminate various proposed mechanisms and feedbacks against the observational data.
9. Change in AMOC strength is an important factor in sea level changes in the North Atlantic. In these AMOC and sea level changes, injection of melt water into the North Atlantic plays a major role. Heat transport associated with AMOC into the Greenland Ice Sheet is an important contributor to its melting. Further studies assessing the impacts of AMOC on the cryosphere, particularly on the Arctic sea ice and the Greenland Ice Sheet are encouraged.
10. Analysis of CMIP3 and CMIP5 model simulations indicate that the surface expression of AMOC variability – the so-called the Atlantic Multidecadal Oscillation (or Variability) – remains unchanged with both the past and the expected 21st century changes in greenhouse gas concentrations.
11. Improved understanding of how AMOC variability affects ocean-atmosphere exchanges of carbon, biogeochemical cycles, and associated changes in marine ecosystems is a near-term priority.

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

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

Task Team 1: AMOC Observing System Implementation and Evaluation

Members	*Institution*
Molly Baringer	NOAA Atlantic Oceanographic and Meteorological Laboratory
Kathleen Donohue	University of Rhode Island
Marieke Femke de Jong	Woods Hole Oceanographic Institution
Gustavo Goni	NOAA Atlantic Oceanographic and Meteorological Laboratory
Patrick Heimbach (Chair)	Massachusetts Institute of Technology
Bill Johns	University of Miami
Felix Landerer	Caltech/NASA Jet Propulsion Laboratory
Craig Lee	University of Washington
Susan Lozier	Duke University
Chris Meinen (Vice-chair)	NOAA Atlantic Oceanographic and Meteorological Laboratory
Thomas Rossby	University of Rhode Island
Uwe Send	Scripps Institution of Oceanography
John Toole	Woods Hole Oceanographic Institution

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

- 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
Gustavo Goni	NOAA Atlantic Oceanographic and Meteorological Laboratory
Sirpa Häkkinen	NASA Goddard Space Flight Center
Kathryn Kelly	University of Washington
Jonathon Lilly	University of Rhode Island
Susan Lozier	Duke University
Julian McCreary	University of Hawaii
Mike McPhaden	NOAA Pacific Marine Environmental Laboratory
Renellys Perez	NOAA Atlantic Oceanographic and Meteorological Laboratory
Peter Rhines	University of Washington
Irina Rypina	Woods Hole Oceanographic Institution
C.K. Shum	Ohio State University
Michael Spall	Woods Hole Oceanographic Institution
Fiamma Straneo	Woods Hole Oceanographic Institution
Luanne Thompson (Vice-chair)	University of Washington
Josh Willis	Caltech/NASA Jet Propulsion Laboratory
Xiao-Hai Yan	University of Delaware
Rong Zhang (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 timescales 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
Wei Cheng	University of Washington
Alan Condron	University of Massachusetts
Gokhan Danabasoglu	National Center for Atmospheric Research
Tom Delworth	NOAA Geophysical Fluid Dynamics Laboratory
Shenfu Dong	University of Miami
Alexey Fedorov	Yale University
Chris Hill	Massachusetts Institute of Technology
Aixue Hu	National Center for Atmospheric Research
Julian McCreary	University of Hawaii
Rym Msadek (Chair)	NOAA Geophysical Fluid Dynamics Laboratory
Robert Pickart	Woods Hole Oceanographic Institution
Tony Rosati	NOAA Geophysical Fluid Dynamics Laboratory
Eli Tziperman	Harvard University
Chunzai Wang	NOAA Atlantic Oceanographic and Meteorological Laboratory
Wilbert Weijer	Los Alamos National Laboratory
Jiayan Yang	Woods Hole Oceanographic Institution
Steve Yeager (Vice-chair)	National Center for Atmospheric Research
Rong Zhang	NOAA Geophysical Fluid Dynamics Laboratory

The team is charged with assessing the physical mechanisms underlying AMOC variability and the potential predictability of the AMOC. Both natural and anthropogenically-induced variations are being pursued. In the near-term, the task team will endeavor to:

- 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
- Contribute to ongoing near-term prediction and predictability efforts using notable AMOC-related climate events for verification.

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

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

Members	*Institution*
Ping Chang	Texas A&M University
Ruth Curry (Vice-chair)	Woods Hole Oceanographic Institution
Sarah Gille	Scripps Institution of Oceanography
Terry Joyce	Woods Hole Oceanographic Institution
Kathryn Kelly	University of Washington
Yochanan Kushnir (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 B: AMOC Projects Active in 2013

PIs	Project	Sponsor	Duration
Molly Baringer (NOAA/AOML) **Sylvia Garzoli** (NOAA/AOML) **Gustavo Goni** (NOAA/AOML)	State of the Climate: Quarterly Reports on the Meridional Heat Transport in the Atlantic Ocean	NOAA	Jun 2005 – Ongoing
Molly Baringer (NOAA/AOML) **Christopher Meinen** (NOAA/AOML) **Sylvia Garzoli** (NOAA/AOML)	Western Boundary Current Time Series (WBTS)	NOAA	Jun 2005 – Ongoing
Nicholas Bates (BIOS) **Rodney Johnson** (BIOS)	The Panulirus Hydrographic Stations: Years 59-64	NSF	Apr 2012 – Mar 2017
Amy Bower (WHOI) **Michael Spall** (WHOI)	A Crossroads of the AMOC: The Charlie-Gibbs Fracture Zone	NSF	Oct 2009 – Sep 2014
Grant Branstator (NCAR) **Haiyan Teng** (NCAR) **Gerald Meehl** (NCAR)	Initial Value Predictability of Intrinsic Oceanic Modes and Implications for Decadal Prediction over North America	DOE	Sep 2010 – Aug 2013
Martha Buckley (AER) **Rui Ponte** (AER) **Jason Furtado** (AER) **Patrick Heimbach** (MIT)	Identifying Mechanisms of AMOC Variability in ECCO State Estimates and CMIP5 Models	NOAA	Sep 2013 – Aug 2016
James Carton (U. Maryland) **Benjamin Diese** (Texas A&M)	SODA: Exploring Centennial Changes in Ocean Circulation	NSF	Jun 2008 – May 2013
James Carton (U. Maryland) **Gennady Chepurin** (U. Maryland) **Sirpa Häkkinen** (NASA/GSFC) **Michael Steele** (U. Washington)	Using Ocean Data Assimilation to Explore Arctic/Subarctic Climate Variability	NSF	Sep 2012 – Aug 2015
Paola Cessi (UCSD/SIO) **Christopher Wolfe** (Stony Brook U.)	Pulling the Meridional Overturning Circulation from the South	DOE	Sep 2010 – Aug 2013
Ping Chang (Texas A&M) **Link Ji** (Texas A&M) **Ben Kirtman** (U. Miami)	Role of Atmospheric Variability in the AMOC	NOAA	Sep 2011 – Aug 2014
Ping Chang (Texas A&M) **Gokhan Danabasoglu** (NCAR) **Steve Yeager** (NCAR)	Understanding Changes in the AMOC during the 20th Century Using IPCC AR5 Model Ensembles	NOAA	Sep 2013 – Aug 2016
Alan Condron (U. Massachusetts) **Raymond Bradley** (U. Massachusetts)	High-Resolution Model Development to Quantify the Impact of Icebergs on the Stability of the AMOC	DOE	Sep 2011 – Sep 2014
Ruth Curry (WHOI) **Kurt Polzin** (WHOI)	Dynamics of Abyssal Mixing and Interior Transport Experiment (DynAMITE)	NSF	Nov 2009 – Oct 2014
Gokhan Danabasoglu (NCAR) **Alicia Karspeck** (NCAR) **Joe Tribbia** (NCAR) **Steve Yeager** (NCAR) **Tom Delworth** (NOAA/GFDL) **Rym Msadek** (NOAA/GFDL) **Tony Rosati** (NOAA/GFDL) **Young-Oh Kwon** (WHOI) **Claude Frankingoul** (WHOI)	A Collaborative Multi-Model Study: Understanding AMOC Variability and their Impacts on Decadal Prediction	NOAA	Sep 2013 – Aug 2016

PIs	Project	Sponsor	Duration
Gokhan Danabasoglu (NCAR) **Jeffrey Andreson** (NCAR) **Grant Branstator** (NCAR) **Keith Lindsay** (NCAR) **Joe Tribbia** (NCAR) **Claude Frankingoul** (WHOI) **Young-Oh Kwon** (WHOI) **Minghua Zhang** (Stony Brook U.)	Mechanisms, Predictability, Prediction, and Regional and Societal Impact of Decadal Climate Variability	NSF	Mar 2013 – Feb 2018
Gokhan Danabasoglu (NCAR) **Joe Tribbia** (NCAR)	The Mechanisms, Predictability, and Climate Impacts of Decadal-Scale AMOC Variability Simulated in a Hierarchy of Models	NOAA	Sep 2009 – Jul 2013
Shenfu Dong (U. Miami) **Gustavo Goni** (NOAA/AOML) **Molly Baringer** (NOAA/AOML) **George Halliwell** (NOAA/AOML)	Assessing the Sensitivity of Northward Heat Transport/AMOC to Forcing in Existing Numerical Model Simulations	NOAA	May 2010 – Apr 2013
Kathleen Donohue (U. Rhode Island) **Charles Flagg** (SUNY/Stony Brook) **Thomas Rossby** (U. Rhode Island)	The Oleander Project: Sustained Observations of Ocean Currents in the NW Atlantic between New York and Bermuda	NSF	Sep 2008 – Aug 2014
Alexey Fedorov (Yale U.)	A Generalized Stability Analysis of the AMOC in Earth System Models: Implication for Decadal Variability and Abrupt Climate Change	DOE	Sep 2011 – Sep 2014
Marieke Femke de Jong (WHOI) **Amy Bower** (WHOI)	Pathways to the Denmark Strait Overflow: A Lagrangian Study in the Iceland Sea	NSF	Sep 2013 – Mar 2018
Sarah Gille (UCSD/SIO) **Doug Martinson** (Columbia U./LDEO)	Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt	NOAA	May 2010 – Apr 2014
Gustavo Goni (NOAA/AOML)	Assessment of the Meridional Overturning Circulation and Meridional Heat Transport and their Meridional Variability in the South Atlantic Ocean	NASA	Jan 2013 – Dec 2016
Gustavo Goni (NOAA/AOML) **Molly Baringer** (NOAA/AOML) **Sylvia Garzoli** (NOAA/AOML)	The Ship of Opportunity Program	NOAA	Ongoing
Patrick Heimbach (MIT) **Rui Ponte** (AER) **An Nguyen** (MIT) **Carl Wunsch** (MIT)	An Eddy-Permitting Arctic and Sub-Polar State Estimate for Climate Research	NSF	Sep 2010 – May 2014
Patrick Heimbach (MIT) **Rui Ponte** (AER) **Carl Wunsch** (MIT)	Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period	NOAA	May 2010 – Apr 2014
Aixue Hu (NCAR)	Influence of the Continental Ice Retreat on Future Global Climate	DOE	Jan 2013 – Dec 2017
Aixue Hu (NCAR)	Uncertainty in Future Regional Sea Level Rise due to Internal Climate Variability	DOE	Jan 2013 – Dec 2017
Bill Johns (U. Miami) **Lisa Beal** (U. Miami) **Christopher Meinen** (NOAA/AOML) **Molly Baringer** (NOAA/AOML)	An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic	NSF	Apr 2003 – Jun 2014
Kathryn Kelly (U. Washington) **LuAnne Thompson** (U. Washington)	Assessing Meridional Transports in the North Atlantic Ocean	NASA	Oct 2008 – Mar 2014
Kathryn Kelly (U. Washington) **LuAnne Thompson** (U. Washington)	Sources and Impacts of Variability of the Meridional Property Transports in the Atlantic Ocean	NASA	Jan 2014 – Dec 2014

PIs	Project	Sponsor	Duration
Kathryn Kelly (U. Washington) **Suzanne Dickinson** (U. Washington)	The Contributions of Ocean Circulation to North Atlantic SST	NASA	Feb 2010 – Jan 2015
Jong Kim (Argonne Nat. Lab) **William Collins** (LBNL)	Investigation of the Magnitudes and Probabilities of Abrupt Climate Transitions	DOE	Jun 2008 – May 2015
Young-Oh Kwon (WHOI) **Claude Frankingoul** (WHOI) **Gokhan Danabasoglu** (NCAR)	Decadal Variability of the AMOC and its Impact on the Climate: Two Regimes and Rapid Transition	NOAA	May 2010 – Apr 2013
Felix Landerer (Cal Tech/JPL)	Variability of the South Atlantic Meridional Overturning Circulation	NASA	Jan 2013 – Dec 2015
Craig Lee (U. Washington) **Richard Moritz** (U. Washington) **Jason Gobat** (U. Washington) **Kate Stafford** (U. Washington)	The Arctic Observing Network at Critical Gateways—A Sustained Observing System at Davis Strait	NSF	Sep 2010 – Aug 2015
Jonathan Lilly (NorthWest Res. Assoc.) **Kathleen Dohan** (ESR) **Thomas Rossby** (U. Rhode Island) **Fiamma Straneo** (WHOI) **Michael Spall** (WHOI)	Mode Water Formation in the Lofoten Basin: A Key Element in the Meridional Overturning Circulation	NSF	Jan 2000 – May 2013
Susan Lozier (Duke U.) **Bill Johns** (U. Miami) **Amy Bower** (HWOI) **Robert Pickart** (WHOI) **Fiamma Straneo** (WHOI)	Overturning in the Subpolar North Atlantic (OSNAP)	NSF	Sep 2013 – Aug 2018
Julian McCreary (U. Hawaii) **Ryo Furue** (U. Hawaii) **Axel Timmerman** (U. Hawaii) **Fabian Schloesser** (U. Hawaii)	Dynamics of the Descending Branch of the AMOC	NSF	Jun 2009 – May 2013
Michael McPhaden (NOAA/PMEL) **Dongxiao Zhang** (NOAA/PMEL) **Wei Cheng** (U. Washington)	Decadal and Multidecadal Variability of the AMOC in Observational Records and Numerical Models	NOAA	May 2010 – Apr 2013
Christopher Meinen (NOAA/AOML) **Sylvia Garzoli** (NOAA/AOML) **Molly Baringer** (NOAA/AOML) **Gustavo Goni** (NOAA/AOML)	Southwest Atlantic MOC (SAM)	NOAA	Oct 2008 – Ongoing
Ceclie Penland (NOAA/ESRL) **Douglas MacMartin** (Cal Tech) **Eli Tziperman** (Harvard U.)	Variability, Stochastic Dynamics, and Compensating Model Errors of the AMOC in Coupled IPCC Models	NOAA	Sep 2013 – Aug 2016
Renellys Perez (NOAA/AOML) **Ricardo Matano** (Oregon State U.) **Sylvia Garzoli** (NOAA/AOML)	South AMOC: Pathways and Modes of Variability	NOAA	Sep 2013 – Aug 2016
Robert Pickart (WHOI) **Michael Spall** (WHOI)	Denmark Straight Overflow Water: A New Paradigm for the Origin of the Deep Western Boundary Current	NSF	Dec 2010 – Nov 2014
Peter Rhines (U. Washington) **Charles Eriksen** (U. Washington)	Analysis of Eddies, Mixing, and Dense Overflows at the Iceland-Faroe Ridge in the Northern Atlantic Ocean Observed with Seagliders	NSF	Sep 2010 – Aug 2014
Peter Rhines (U. Washington) **Sirpa Häkkinen** (NASA/GSFC)	Improved Estimates of Atlantic Meridional Circulation from Altimetry with Tracers, Drifters, Gliders and Argo Floats	NASA	Jan 2013 – Dec 2016
Thomas Rossby (U. Rhode Island) **Charles Flagg** (SUNY/Stony Brook)	The Norröna Project: An International Collaboration for Sustained Studies of the Meridional Overturning Circulation between Denmark, the Faroes and Iceland	NSF	Aug 2011 – Jul 2015

PIs	Project	Sponsor	Duration
Irina Rypina (WHOI) **Lawrence Pratt** (WHOI)	Transport Pathways in the North Atlantic: Searching for Throughput	NSF	Mar 2012 – Feb 2015
Ramalingam Saravanan (Texas A&M) **Ping Chang** (Texas A&M)	Understanding Climate Model Biases in Tropical Atlantic and Their Impact on Simulations of Extreme Climate Events	DOE	Sep 2010 – Aug 2013
Andreas Schmittner (Oregon State U.) **Aixue Hu** (NCAR) **Sebasitan Mernild** (LANL)	Modeling Effects of Greenland Ice Sheet Melting on AMOC Variability and Predictability	NOAA	Sep 2013 – Aug 2016
Uwe Send (UCSD/SIO)	Meridional Overturning Variability Experiment (MOVE)	NOAA	Jun 2005 – Ongoing
C.K. Shum (Ohio State) **Yuchan Yi** (Ohio State)	Satellite Monitoring of the AMOC	NASA	Mar 2009 – Feb 2013
Michael Spall (WHOI)	Forced Transients in Water Mass Transformation and the Meridional Overturning	NSF	Sep 2012 – Aug 2016
Fiamma Straneo (WHOI) **Steven Lentz** (WHOI)	From Rivers to the Ocean: The Dynamics of Freshwater Export from Hudson Strait	NSF	Apr 2008 – Mar 2014
Fiamma Straneo (WHOI) **Gordon Hamilton** (U. Maine) **David Sutherland** (U. Washinton) **Leigh Sterns** (U. Kansas)	Glacier-Ocean Coupling in a Large East Greenland Fjord	NSF	Aug 2009 – Jan 2015
John Toole (WHOI) **Michael McCartney** (WHOI) **Ruth Curry** (WHOI) **Terrence Joyce** (WHOI) **William Smethie, Jr.** (Columbia U./LDEO)	Line W: A Sustained Measurement Program Sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39N	NSF	May 2003 – Feb 2014
Anastasios Tsonis (U. Wisconsin) **Gregory Duane** (U. Colorado)	An Interactive Multi-Model for Consensus on Climate Change	DOE	Sep 2011 – Aug 2014
Eli Tziperman (Harvard U.) **Douglas MacMartin** (Cal Tech)	Improving Interannual Prediction Skill in a Changing Climate via the Identification of Compensating Coupled Model Errors	DOE	Nov 2010 – Oct 2013
Chunzai Wang (NOAA/AOML) **David Enfield** (NOAA/AOML)	Relationship of the Atlantic Warm Pool with the AMOC	NOAA	Jun 2011 – May 2014
Wilber Weijer (LANL)	Agulhas Leakage and its Impact on the Atlantic Meridional Overturning Circulation in the CCSM4	DOE	Jun 2012 – Aug 2013
Xiao-Hai Yan (U. Delaware) **Young-Heon Jo** (U. Delaware)	Satellite Multi-Sensor Studies of Deep Ocean Convection in the North Atlantic Ocean	NASA	Mar 2009 – Feb 2014
Jiayan Yang (WHOI) **Lawrence Pratt** (WHOI)	Atmospheric Forcing of Marginal-Sea Overflows	NSF	Sep 2009 – Aug 2013
Jianjun Yin (U. Arizona) **Steve Griffies** (NOAA/GFDL) **Shaoqing Zhang** (NOAA/GFDL)	Signature of the AMOC in the North Atlantic Dynamic Sea Level	NOAA	Sep 2013 – Aug 2016
Rong Zhang (NOAA/GFDL) **Tom Delworth** (NOAA/GFDL) **Keith Dixon** (NOAA/GFDL) **Isaac Held** (NOAA/GFDL) **Yochanan Kushnir** (Columbia U./LDEO) **John Marshall** (MIT) **Yi Ming** (NOAA/GFDL) **Rym Msadek** (NOAA/GFDL) **Tony Rosati** (NOAA/GFDL) **Mingfang Ting** (Columbia U./LDEO) **Gabe Vecchi** (NOAA/GFDL)	Have Aerosols Caused the Observed Atlantic Multidecadal Variability?	NOAA	Apr 2012 – Apr 2013

Appendix C: Annual AMOC Project Reports

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

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

This project supports the development of a methodology to estimate heat transport variability using data collected along two High Density Expendable Bathythermograph (XBT) transects operated by NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), satellite data (altimeter and scatterometer), wind products from the National Center for Environmental Prediction (NCEP) reanalysis and products from general circulation models. Quarterly reports estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic are posted on the AOML web site.

Recent results

- Estimates of the heat transport across the North and South Atlantic continue to be posted on the AOML web site, typically within 2 months of the completion of any given cruise.
- This year the MHT in the South Atlantic was highlighted in three publications:
  - Garzoli et al. (2012) examined the properties of the meridional overturning circulation (MOC) and associated meridional heat transport (MHT) and salt fluxes are analyzed in the South Atlantic using data collected along 27 sections at nominally 35°S for the period of time 2002 to 2011, and Argo profile data collected in the region.
  - Baringer et al. (2013) extended this time series through 2013 and compared it to the ECCO2 State estimation model.
  - Macdonald and Baringer (2013) compared the 35°S XBT derived meridional heat transport estimates to the estimates at 26°N and 41°N.
- Ongoing analysis includes estimating the differences between in situ heat transport estimates and model-based estimates. In addition, the project is extending observational estimates to include satellite derived synthetic XBT profiles and hence longer monthly time series estimates along 20°S, 25°S, 30°S, and 35°S back to 1992.
- An expansion of this program could include the analysis of all in situ data (not just XBT data) to determine the physical processes involved in meridional heat and mass transport throughout the Atlantic Ocean.

Online data

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

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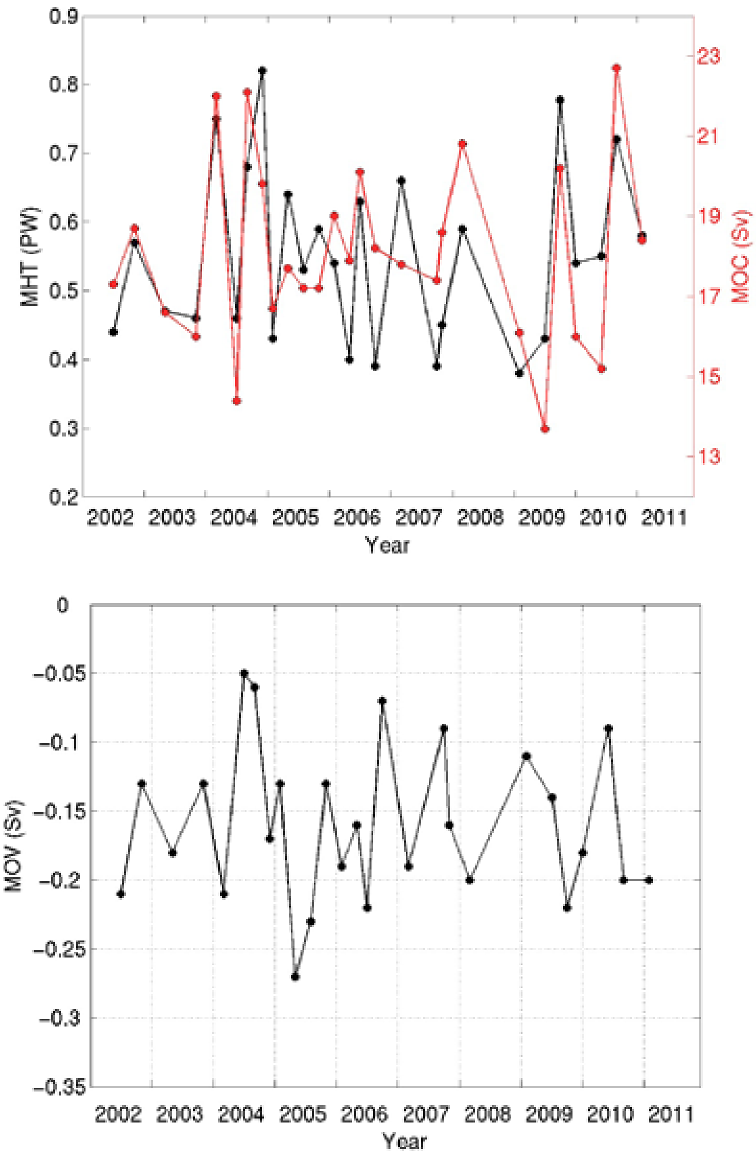

Figure 1. *Top:* Time series of the MHT (black) and the AMOC (red) along nominally 35°S for the time period 2002 to 2011. *Bottom:* Time series of the Mov nominally across 35°S for the time period 2002. Values are negative contrary to model results indicating that the MOC is bistable (Garzoli et al. 2013).

Western Boundary Time Series

PIs: M. Baringer[1], C. Meinen[1], S. Garzoli[2,1]
US Collaborators: B. Johns[3]
International Collaborators: D. Smeed[4], H. Bryden[4], E. Frajka-Williams[4], S. Cunningham[5]
[1]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
[2]University of Miami, Miami, FL
[3]University of Miami, Miami, FL
[4]National Oceanography Centre, Southampton, UK
[5]Scottish Marine Institute Oban, Argyll, UK

This project continuously monitors two important components of the thermohaline circulation in the Subtropical North Atlantic with the ultimate goal of determining the state of the overturning circulation and providing a monitoring system for rapid climate change and hence addresses the program deliverable on "ocean heat content and transport". The components include the northward flowing Florida Current and the southward flowing Deep Western Boundary Current.

Recent results

While this program only funds data collection this past fiscal year, six papers were published related to this project (Baringer et al. 2013, Frajka-Williams, et al. 2013, McCarthy et al. 2013, Meinen et al. 2013, Srokosz et al. 2013, Szutz and Meinen 2013), two papers were accepted (Macdonald and Baringer 2013, Smeed et al. 2013), and two data reports were published (Hooper and Baringer 2013a, Hooper and Baringer 2013b). The published papers included the following highlights:

- Baringer et al. (2013) state of the meridional overturning circulation report appeared in the State of the Climate Report that expanded the report to include 41°N, 26°N, 16°N and 35°S meridional transports of heat and MOC as well as the Florida Current time series.
- Frajka-Williams et al. (2013) used WBTS data in combination with satellite altimetry to show coherent changes in the Florida Current volume transport and changes in both the Antilles Current offshore of the Bahamas as well as eddy signatures propagating west from the basin interior.
- Szutz and Meinen (2013) calibrated the Florida Current voltage data into a salinity transport.
- McCarthy et al. (2012) showed that the low meridional overturning event in the winter of 2009-2010 was caused largely by unusually low southward transport in the basin interior, supplemented by anomalous southward Ekman transport and a slightly lower than usual Florida Current transport.
- Meinen et al. (2012) extended the Deep Western Boundary Current time series using a combination of conventional moorings and PIES. This study showed little annual variability, large meso-scale variability and confirmed the robustness of transport estimates from PIES alone.
- Srokosz et al. (2012) summarize the state of the knowledge about observations and modeling of the meridional overturning circulation that highlighted the results from the joint US/UK science meeting held in July 2011. Central to this paper were results from the Western Boundary Time Series project.

Online data

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

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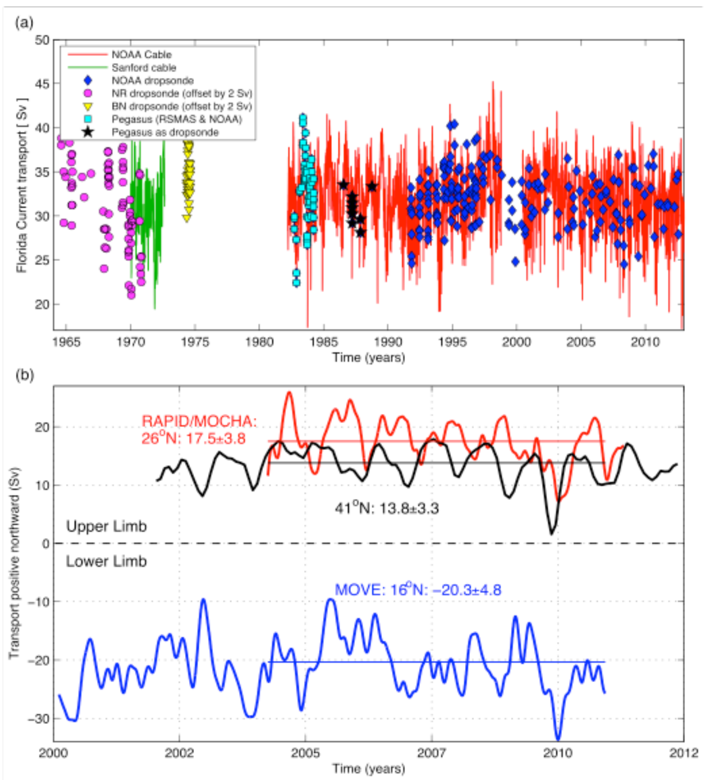

Figure 1. Volume transport in Sverdrups (Sv; where 1 Sv = 10^6 m^3 s^{-1}) of the Florida Current between Florida and the Bahamas, from dropsonde measurements (symbols) and cable voltages (continuous line), extending the time-series shown in Meinen et al. (2010) (b) AMOC transport estimates (Sv). *Red:* RAPID/MOCHA at 26.5°N: A direct measure of the upper and lower limbs of the AMOC. *Black:* 41°N an index of maximum AMOC strength from Argo float measurements in the upper 2000 m only, combined with satellite altimeter data. *Blue:* MOVE at 16°N: Transport of North Atlantic Deep Water in the lower limb of the AMOC between 1100m and 4800m depth between the Caribbean and the mid-Atlantic Ridge. The temporal resolution of the three time-series is ten days for 16°N and 26°N and one month for 41°N. In this figure the data have been three month low-pass filtered. The means and standard deviations for the common period of April 2, 2004 to April 1, 2010 are marked on the figure and indicated by the horizontal line on each time-series.

The Panularis Hydrographic Stations: Year 60-64

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

Sampling program

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

Recent results

For this current award (April 2013 to March 2014), a total of 23 additional hydrographic stations have been performed at the nominal Hydrostation S site, increasing the total number of stations to 1243 as of March 5, 2014. All cruises during this current period were conducted on the BIOS R/V Atlantic Explorer with a station frequency ranging between 7 to 21 days and most stations consisting of two CTD casts. Hydrostation S data have played a central role in understanding the seasonal and longer-term variations of hydrography and biogeochemistry in the Sargasso Sea as outlined in the four themes above (Bates et al., 2012, 2014). Several hundred papers have cited Hydrostation S data, and these papers have been cited more than 40,000 times.

Online data

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

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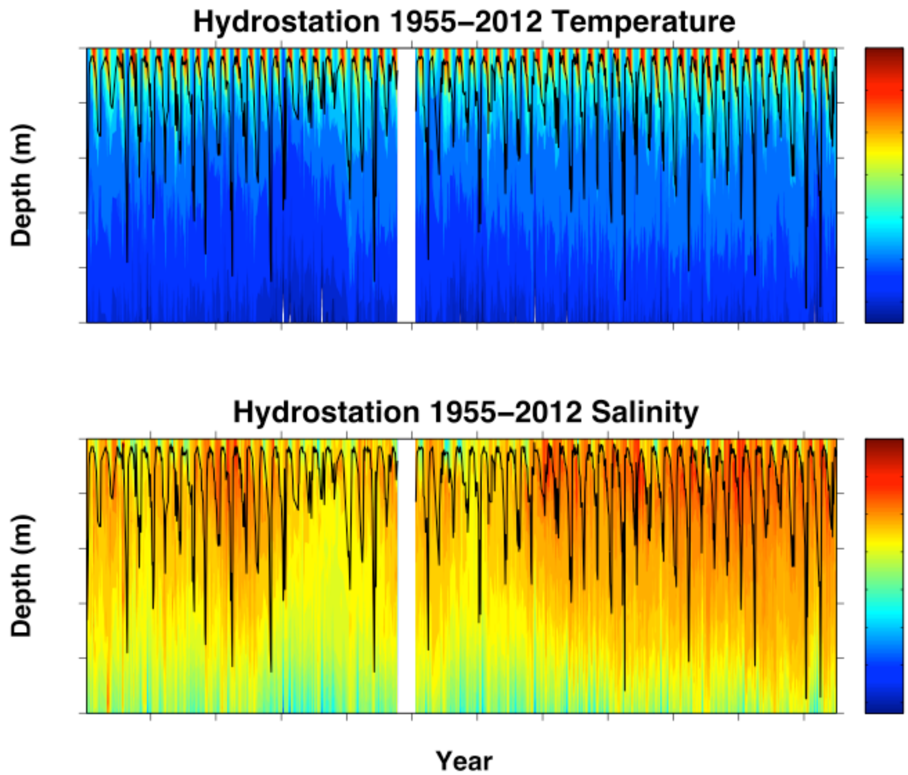

Figure 1. Contour plots of (a) temperature and (b) salinity for Hydrostation S from January 1955 through July 2012. Mixed layer depth overlaid as the black line and is computed using the variable sigma_T method (Sprintall & Tomczak, 1992). Data through December 2011 are available through http://bats.bios.edu, while data from Jan 2012 – July 2012 are currently available as preliminary data ftp://ftp.bios.edu/BATS/prelim/ although have been fully processed and quality controlled for release pending post calibrations of the CTD sensors. These more recent data will be available as final data on June 15, 2013. The data gap from January 1979 through April 1980 represents the period where the hydrowire with all Nansen bottles and reversing thermometers was lost at sea and resources were not available for immediate replacement.

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

PIs: A. Bower and M. Spall
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The objective of this program is to obtain an improved direct estimate of the mean and low frequency variability of the deep westward transport of Iceland-Scotland overflow water (ISOW) through the Charlie-Gibbs Fracture Zone (CGFZ) and to gain a better understanding of the causes of the low frequency variability and the influence of ridge fracture zones on the larger scale oceanic circulation.

Recent results

In the past year, all of the data from the two-year, eight mooring array deployed across the CGFZ in 2010-2012 (Figure 1) was processed, including that from microcats, current meters, and moored profilers. Data return was nearly 100%. This two-year time series from eight moorings provides the first long-term simultaneous observations of the hydrographic properties and transport of ISOW entering the western North Atlantic through the CGFZ. Using the isohaline 34.94 to define the ISOW layer, a preliminary calculation of the two-year mean and standard deviation of ISOW transport was -1.7 ± 1.5 Sv, compared to -2.4 ± 3.0 Sv reported by Saunders for a 13-month period in 1988-1989 using the same isohaline. Differences in the two estimates could reflect the difficulty of defining the long-term mean in the presence of strong transport variability on multiple time scales: ten, 13-month mean transport estimates from the two-year record range from -2.0 to -1.4 Sv. Furthermore, the temperature/salinity time series indicate large fluctuations in ISOW layer thickness, for example, the thickness over the northern rift valley had a mean value of about 1400 m and ranged from 400 to 2100 m (compared to Saunders' fixed value of 2200 m at this site). Another factor being considered is the possible change in salinity of ISOW over the intervening years.

An idealized numerical model for the flow between two gaps in zonally offset ridges has been developed. For gaps that are located at different latitudes, and in the linear limit, the flow forms a western boundary current along the western ridge, which separates at the latitude of the eastern gap, forming a narrow zonal jet. As nonlinearity is increased the flow becomes time dependent, but in the mean, the flow still flows in a western boundary current along the western ridge to the outflow latitude of the eastern gap. Vorticity production in a viscous sublayer produces anomalous potential vorticity, which is advected into the basin interior by the separated boundary current. This results in a quasi-periodic state of westward propagating meanders in the interior and large meridional excursions of the separation point of the western boundary current, similar to what is observed for the East Australia Current near the southern tip of Australia and west of New Zealand. It is also consistent with the separation of the North Atlantic Current at the latitude of the CGFZ. A scaling theory for the amplitude and frequency of the oscillation is derived from consideration of the vorticity budget in the viscous sublayer and wave dynamics in the interior. Quantities diagnosed from the numerical model compare well with the scaling theory over a wide range of parameter space (Figure 2).

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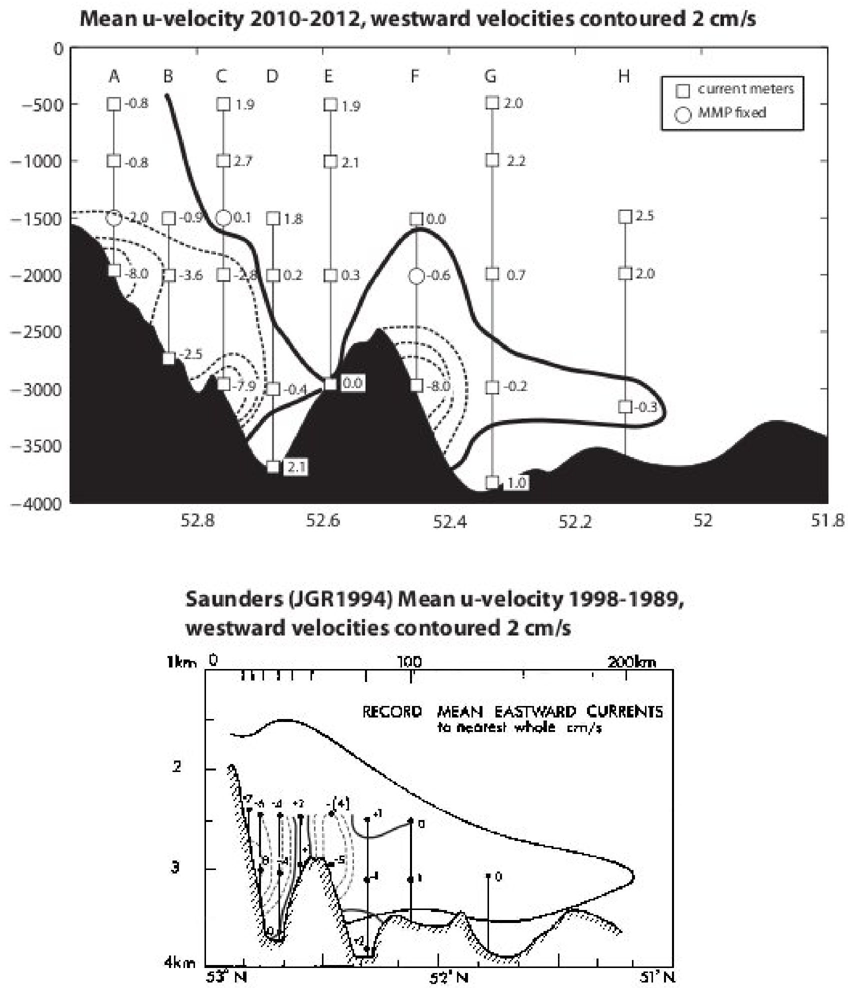

Figure 1. *Upper:* U-velocity measured by the 2010-2012 mooring array instruments. Only the westward velocity is hand-contoured, at 2 cm/sec intervals. Thickest black line is the approximate location of the 0 cm/sec contour. *Lower;* The same, but for the 1988-1989 Saunders (JGR, 1994) moorings. Both u-velocity sections show highest velocities along the north walls of the two channels of the fracture zone. The 2010-2012 moorings extended farther north along the ridge, and higher into the water column, and capture a third high velocity core at about 2000 m depth at Mooring A.

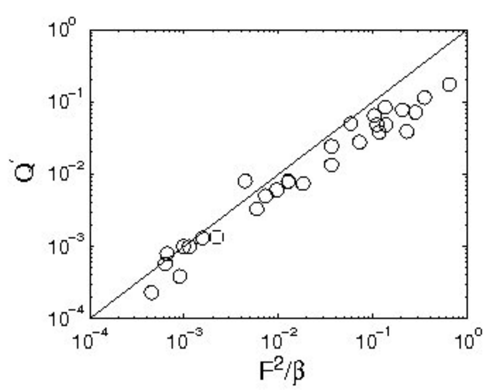

Figure 2. Comparison between the non-dimensional basin averaged potential vorticity variance Q′ produced by a numerical model and that predicted by a scaling theory that balances vorticity production in the western boundary viscous sub-layer and wave advection in the basin interior. Each circle represents a different model calculation in which model parameters have been varied (Coriolis parameter, reduced gravity, variation in planetary vorticity, basin dimensions).

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

PIs: G. Branstator[1], H. Teng[1], G. Meehl[1]
International Collaborators: A. Gritsun[2]
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The objective of this program is to quantify the predictability characteristics of the climate system as simulated by comprehensive climate models on decadal timescales. The focus is on the predictability of prominent or highly predictable patterns, and to determine whether the identified decadal predictability has a signature over North America.

Recent results

The recent work has had two goals. The first is to quantify the predictability of AMOC in nine models, eight of which participated in CMIP5, and to compare it to the predictability of North Atlantic heat content. Here, the term 'predictability' is used to refer to the intrinsic uncertainty in predictions that results from the chaotic nature of climate models, as quantified in perfect model experiments. The aim of this work is to determine whether AMOC's predictability is high enough to potentially positively impact the predictability of heat content. The methods used allow for the estimation of predictability through analysis of long control runs rather than employing the usual perturbation ensemble method. This has made it possible to consider the average behavior of hundreds of start dates for each model. It has also been determined whether there are special patterns of variability that have predictability that is substantially greater than the average predictability of generic fluctuations. Significant findings from this research include:

- For all but one model annual mean AMOC is less predictable than annual mean upper 500 m heat content.
- The limit of predictability varies substantially from one model to another; annual mean AMOC becomes essentially unpredictability after four to 20 years depending on model, while heat content becomes unpredictable after five to well over 20 years.
- Time averaging affects the predictability of AMOC more than heat content with five and ten year average AMOC actually being more predictable than heat content.
- There are special AMOC and heat content patterns that are much more predictable than typical patterns. For example, for these patterns a threshold of predictability that is typically reached after two years when full AMOC fields are considered is not reached until forecast year ten.

The second goal is to develop and apply a method for determining surface forcing distributions that optimally excite the underlying ocean on decadal time scales. The responses to these distributions are of interest because they have the potential to have large signals. To find these optimal forcing and response patterns, operators have been used that are constructed using the Fluctuation Dissipation Theorem. These linear operators give the response of a full nonlinear model at a specified range to a forcing of arbitrary structure, provided the forcing is sufficiently weak. To date, such operators have been constructed for a low-resolution version of NCAR's CESM and then used to find the salinity forcing that produces the strongest AMOC response. Preliminary tests suggest that the operators are giving good approximations to the response of the full GCM and thus can be used to solve optimal forcing/response problems.

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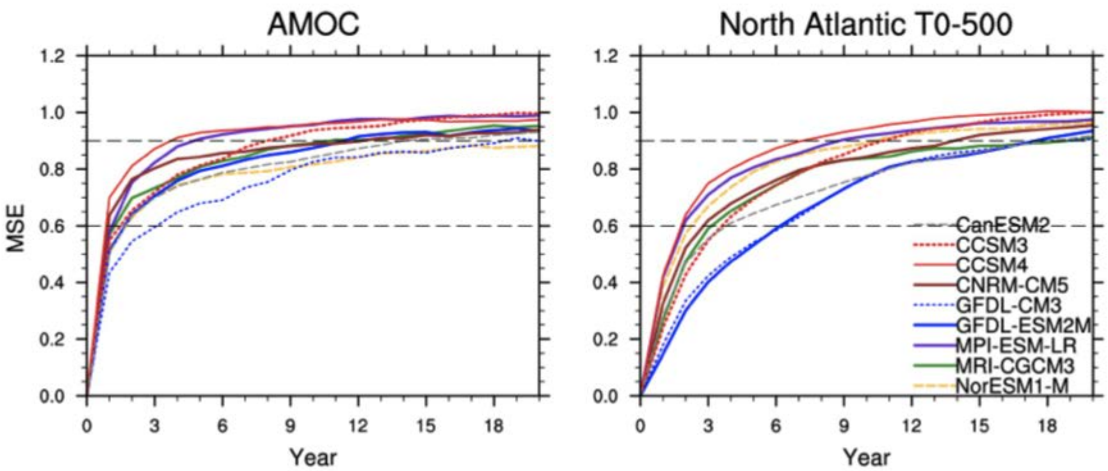

Figure 1. Predictability of various CGMs, including 8 CMIP5 models, for AMOC and North Atlantic 0-500 m heat content. The plotted quantity, which is given as a function of forecast range, is the ratio of a squared measure of the spread in ensembles of states that are initially very similar to the spread of randomly drawn states from control integrations.

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

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The project focuses on two main science questions: (1) on what timescales is the AMOC coherent with latitude and what does this coherence imply about mechanisms of AMOC variability and the predictability of the AMOC on various timescales? (2) What is the relationship between AMOC variability and low-frequency SST variability? Does the AMOC play an active role in setting SST on interannual to decadal timescales and what are possible implications for predictability of Atlantic SSTs? To answer these questions, the project conducts detailed analyses of dynamical mechanisms of AMOC variability in data-constrained, dynamically and kinematically consistent estimates of the global circulation (Estimating the Circulation and Climate of the Ocean, ECCO), and evaluates these mechanisms in multi-model comparisons (CMIP5 models).

Recent results

Meridional coherence of the AMOC:

In accord with results of Bingham et al. (2007), the AMOC and the Atlantic ocean heat transport (OHT) are found to be meridionally coherent throughout the tropics and subtropics (including across the equator), but there is a break in coherence at the subtropical/subpolar gyre boundary (Wunsch and Heimbach, 2013).

In contrast to the theoretical expectation of seasonal AMOC and OHT variability (e.g. Jayne and Marotzke, 2001), seasonal AMOC and Atlantic OHT variability are not found to be coherent across the equator. Instead, the seasonal signal is dominated by large AMOC/OHT anomalies in the Northern Hemisphere tropics, which appear to be related to boundary current variability rather than Ekman transport variability.

Relationship between AMOC variability and North Atlantic upper-ocean heat content variability:

North Atlantic upper-ocean heat content (UOHC) exhibits significant low-frequency variability. The goal is to determine the portion of this UOHC variability that is due to active ocean dynamics, such as the AMOC. To explore this question the project utilizes the ECCO state estimate (1992-2010) to quantify the upper ocean heat budget in the North Atlantic on monthly to interannual timescales (seasonal cycle removed). Three novel techniques are introduced: (1) the heat budget is integrated over the maximum climatological mixed layer depth (integral denoted as H), which gives results that are relevant for explaining SST while avoiding strong contributions from vertical diffusion and entrainment; (2) advective convergences are separated into Ekman and geostrophic parts, a technique that is successful away from ocean boundaries; and (3) air-sea heat fluxes and Ekman advection are combined into one "local forcing" term. The central results of the analysis are as follows: (1) in the interior of subtropical gyre, local forcing explains the majority of H variance on all timescales resolved by the ECCO estimate; (2) in the Gulf Stream region, low-frequency H anomalies are forced by geostrophic convergences and damped by air-sea heat fluxes; and (3) in the interior of the subpolar gyre, diffusion and bolus transports play a leading order role in H variability, and these transports are correlated with low-frequency variability in wintertime mixed layer depths.

These results suggest that the AMOC does not play an active role in setting UOHC anomalies in the subtropical gyre on the timescales resolved by the ECCO estimate. In contrast, ocean dynamics, perhaps including OHT convergence variability due to AMOC variability, play a role in setting UOHC in the Gulf Stream region and the subpolar gyre.

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Collaborative Research: Using Ocean Data Assimilation to Explore Arctic/Subarctic Climate

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The first objective of this program is to develop improved understanding of what past oceanic changes have occurred at high latitude to extend the Simple Ocean Data Assimilation (SODA) ocean reanalysis as a tool for high latitude research. The second objective is to examine these results to explore the physical processes governing interaction between the oceanic changes, including basin exchanges, and exchanges with the overlying atmosphere, and how these processes may contribute to climate variability.

Recent results

- The project has begun development of a hybrid sequential data assimilation filter. The development and implementation of this filter was the subject of S. Penny's dissertation, co-advised by E. Kalnay, and is described in Penny et al. (2013a). A second paper describes a hybrid approach, combining 3DVar and ensemble filters (Penny 2013b).

- The project has begun looking at the tide gauge dataset in comparison with currently available ocean reanalyses/syntheses. The results of this comparison are summarized in a paper in press (Chepurin et al. 2014).
- The project has begun looking at the role of decadal variations in aerosols on the ocean circulation through analysis of the CMIP5 coupled model responses to volcanic aerosols. This work, led by a graduate student at University of Maryland, has been written up and is also under submission (Ding et al. 2014).

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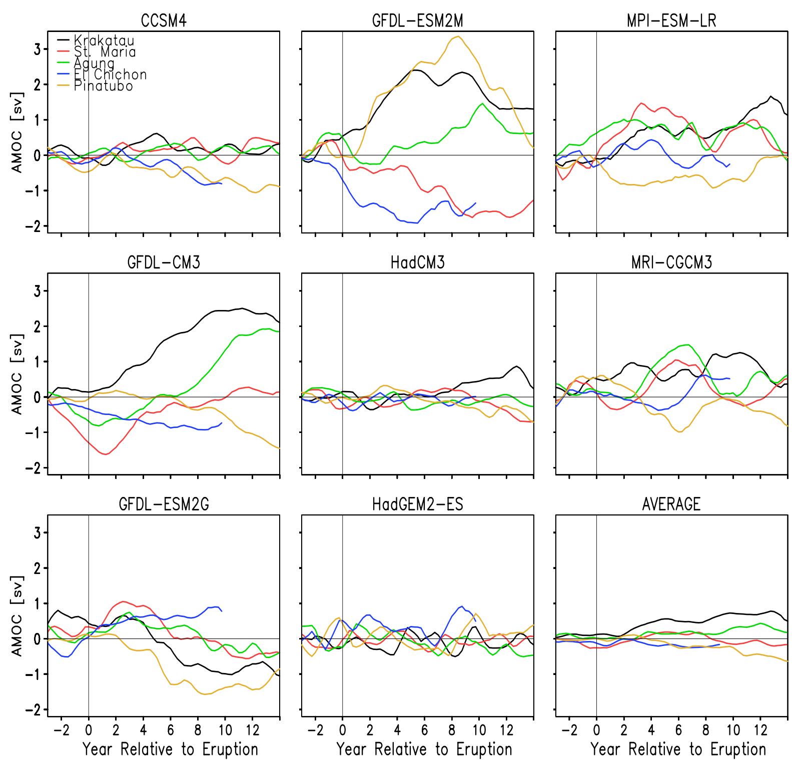

Figure 1. Ensemble mean Atlantic meridional overturning streamfunction anomaly from the six-year average prior to each of the five major tropical eruptions since 1870 (units: Sv) for ensembles of historical simulations (all forcing) from eight CMIP5 models. The time series have been smoothed with a running eight-season average after removal of the climatological seasonal cycle. Anomalies are computed relative to the 2-year average prior to eruption. Lower right-hand panel shows the average of all the ensembles from the different models for each eruption. The El Chichón time series are truncated so they do not continue past the 1991 Pinatubo eruption. Note the weak acceleration of AMOC for some of the volcanoes that lags the eruptions by 5-10 years. A more complete analysis indicates the acceleration is due to increases in the density of surface water at high latitude due to cooling and rainfall changes (Ding et al. 2014)

Pulling the Meridional Overturning Circulation from the South

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

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

Recent results

- The project has shown that freshwater feedbacks in the adiabatic AMOC increase the range of surface buoyancy values that are shared between the ACC region and the high latitudes of the Northern Hemisphere, leading to a strengthening of the AMOC, compared to that obtained with thermal forcing only. This leads to a stronger ROC compared to the corresponding case without salinity forcing.
- The project has shown that freshwater feedbacks in the adiabatic AMOC can lead to multiple equilibria where the residual overturning is either reinforced or shut down. Self-sustained multidecadal oscillations are observed with amplitudes that increase as the critical forcing for AMOC shutdown is approached. These oscillations mediate the transition between AMOC "on" and "off" states (Figure 1).

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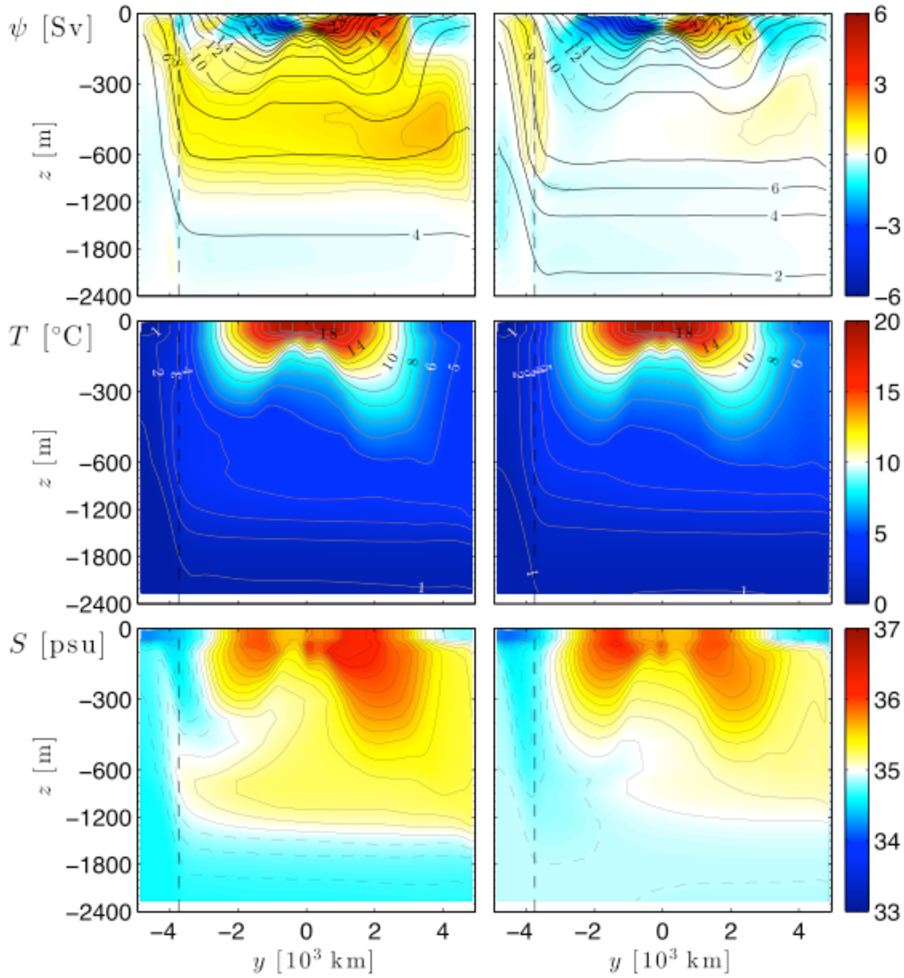

Figure 1. The upper panels give the residual stream function, middle panels the zonally averaged temperature, and the lower panels the zonally averaged salinity. The left panels are for the "on" state and the right panels are for the "off: state. Both states have the same fresh water flux symmetric around the equator, but the surface temperatures differ slightly: the "on" state has DT = 4°C while the "off" state has DT = 5˚C, where DT is the pole-to-pole temperature difference. The equator-to-pole temperature difference (from the south pole to the equator) is 20˚C. The diffusivity below the mixed layer is 3 x 10^{-6} m^2/s. The thick contours in the upper panels give contours of the effective buoyancy field in units of 10^{-3} m/s^2; the thin contours are for the ROC and the contour interval is 0.5 Sv. The vertical dashed line denotes the northern edge of the reentrant channel. The contour intervals in the middle and bottom panels are 1˚C and 0.1 psu, respectively.

Role of Atmospheric Internal Variability in the Atlantic Meridional Overturning Circulation

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[2]University of Miami, Miami, FL

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

Recent results

A major portion of the proposed research, that involves testing the two scientific hypotheses, has been completed:

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.

The following research tasks have been accomplished as described in the proposal:

- Analysis of CCSM3 interactive ensemble (IE) simulations: A detailed analysis of a long IE simulation using CCSM3 has been completed and the results compared to a long CCSM3 control simulation. The results suggest that AIV in the North Atlantic has a controlling effect on AMOC strength and variability (Figure 1).
- CCSM3 IE global warming simulations: A CCSM3 IE simulation under a global warming scenario has been completed and the simulation results are currently being analyzed.
- 20th Century reanalysis studies: An analysis of several 20th century reanalysis products have been completed, including 20CRv2 by Compo et al. (2011) and the SODA dataset by Giese et al. (2011). The results show that there is an increasing trend in both the Atlantic storm track and the AMOC strength, suggesting that the change in the storm track may contribute to the change in the AMOC.
- Ocean—sea ice simulations using the Parallel Ocean Program model version 2 (POP2): A set of POP2 ocean—sea ice simulations have been completed with an alteration in the high-frequency component of the surface wind forcing related to the North Atlantic storm tract variability. The results further confirm the importance of storm track variability in maintaining the strength and variability of the AMOC. This modeling study forms a portion of W. M. Kim's Ph.D. dissertation research. Kim successfully defended his dissertation in January 2013. The study was presented in the US AMOC science team meeting last year.

In one of the related modeling studies, the project investigated the impact of the mid-latitude model SST biases of the Gulf Stream Extension on the North Atlantic storm track using a high-resolution regional model. The result shows that the error in the representation of the Gulf Stream separation can have a significant impact on the Atlantic storm track and associated extreme climate events, including regional storm frequency, extreme precipitation, and surface wind intensity. As the simulation of the Gulf Stream separation improves with the enhanced ocean-model resolution, the sharpened SST front causes a northward shift of the winter storm track in upper levels as the synoptic disturbances propagate eastward. The northward shift of the storm track leads to a 25-30% increase in the simulated storm frequency near the coastal region of northeastern US and a 10~15% decrease near the Mediterranean sea region, as well as significant changes in the extreme precipitation and surface wind intensity along the northern and southern flanks of the storm track, respectively. These results suggest that an accurate representation of the Gulf Stream in climate models has important implications for improving simulation skill of extreme climate events in the North Atlantic sector. These results have been written as a paper to be submitted to Journal Climate for publication.

In another related study, the project analyzed and compared low-frequency variability of winter extreme surface heat flux events associated with cold-air outbreaks (CAOs) in the Kuroshio Extension Region (KER) of the Northwestern Pacific and the Gulf Stream Region (GSR) of the Northwestern Atlantic, using NCEP-CFSR (1979-2009), NCEP-NCAR (1948-2009) and NOAA 20th Century (1910-2009) reanalysis data. In both these regions, a small number of high flux event days contribute significantly to the total turbulent heat fluxes in the entire winter season, and interannual and long-term variations of winter sensible and latent heat flux are determined by the high flux events, which contribute about 80% to the total variance of surface turbulent heat fluxes. However, there are important differences between Pacific and Atlantic CAOs. Generally, the Atlantic CAOs occur with stronger intensity than those in the Pacific. Furthermore, the Pacific CAOs are correlated with the Pacific Decadal Oscillation, but no statistically significant relationship is found between the Atlantic CAOs and the North Atlantic Oscillation. This study forms a part of X. Ma's Ph.D. dissertation research and has been written as a paper to be submitted to Journal Climate.

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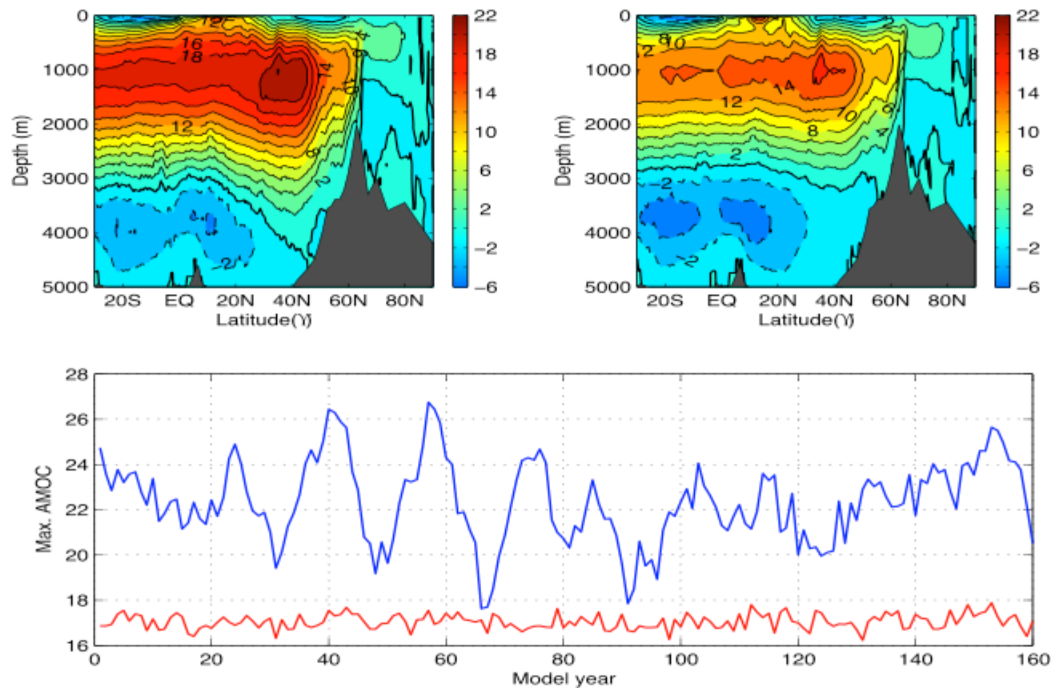

Figure 1. A 160-year time mean AMOC streamfunctions from the control (upper left panel) and IE (upper right panel) simulations. Contour interval is 2 Sv. Time series of the maximum of AMOC streamfunctions (bottom panel) from control (blue) and IE (red) simulations.

Collaborative Research: Understanding Changes in the Atlantic Meridional Overturning Circulation (AMOC) During the 20th Century Using IPCC AR5 Model Ensembles

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This collaborative research between TAMU and NCAR aims at understanding the inconsistency between the simulated AMOC trends in CMIP5 coupled model and CORE-II ocean–sea ice model simulations of the 20th century climate. The proposed research consists of a comprehensive inter-model comparison analysis of IPCC AR5 coupled climate model simulations and ocean—sea ice model simulations of the 20th century climate and a set of ocean—sea ice model sensitivity experiments to assess the sensitivity of long-term AMOC changes to a variety of alternative atmospheric state choices. The first year investigation focuses on the inter-model comparison analysis.

Recent results

Work at TAMU has led to a thorough investigation of the simulated AMOC trends during the last half of 20th century between an ensemble of CCSM4 historical (20th century) runs and a 60-year (1948-2008) CORE-II forced POP2 simulation. It is found that the simulated AMOC trends over the past several decades are opposite in the two model simulations with CCSM4 showing a weakening of the AMOC, while POP2 displaying a strengthened AMOC (Figure 1). A detailed analysis reveals that the opposite AMOC trends are closely related to the opposite sensible heat flux trends over the Labrador Sea (LS) in the two model simulations. In the CORE-II forced POP2 simulation, the sensible heat flux shows an upward trend, mainly resulting from a cooling trend of the surface air temperature over the LS associated with a positive North Atlantic Oscillation (NAO) trend during the past decades. The enhanced sensible heat flux strengthens LS convection, causing a strengthening in the AMOC. In the CCSM4 simulations, the air temperature over the LS region shows a greater warming trend than that of the sea surface temperature, leading to a negative sensible heat flux trend, which causes an increase in the upper ocean buoyancy and a decrease in LS convection. Further analysis shows that there is no positive NAO trend in the CCSM4 simulations as in observations, suggesting that the difference in the simulated AMOC is likely attributed to the different NAO behavior in CCSM4 and observations. The result of the study has been written as a paper to be submitted to Journal Climate. At the present, these analyses are being extended to other CMIP5 model and corresponding ocean model simulations. The plan is to conduct investigations into the relationship between the Atlantic storm track and the NAO.

Work at NCAR has thus far focused on analysis of the CORE-II (Coordinated Ocean-ice Reference Experiments phase II) forced ocean–sea ice simulations of the period from 1948-2007. The project has been using solutions from these hindcast experiments from 18 participating models whose mean AMOC representations are documented in Danabasoglu et al. (2013). A finding, which is robust across most CORE-II simulations, is that the upward trend in AMOC – seen in the latter decades of the 20th century – is related to trends in deep convection in the LS. Yeager and Danabasoglu (2013) have traced the decadal-scale variability in deep mixing in the NCAR CORE-II simulation to slow trends in near-surface atmospheric temperature and humidity over the LS region (Figure 2). The historical atmospheric state changes in this key region set the buoyancy forcing and associated convection anomalies, which are the ultimate source of decadal-scale AMOC variations in the control hindcast. The project is presently exploring the relationship between the 1970-1990 trend towards colder, drier wintertime LS conditions in atmospheric reanalysis and long-term changes in the storm track, and then will evaluate whether comparable decadal trends can be identified in a large ensemble of 20th century simulations, which are being run with the fully-coupled Community Earth System Model (CESM). Work is underway to extend forced ocean–sea ice hindcasts back in time to the beginning of the 20th century, to better facilitate comparison with externally forced coupled simulations of the 20th century. The project is also developing new techniques to isolate synoptic-scale buoyancy forcing of the Atlantic circulation in both uncoupled and coupled simulations.

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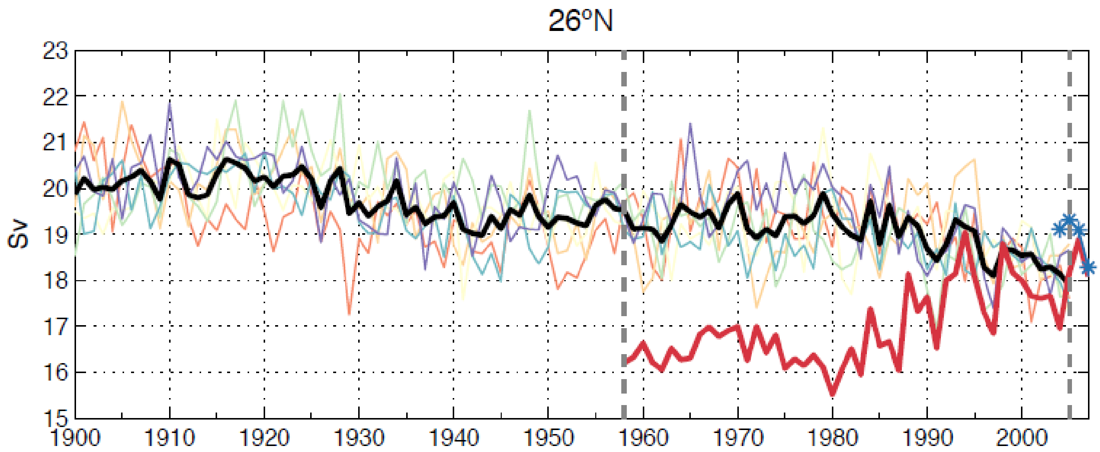

Figure 1. Time series of maximum overturning streamfunction at 26°N in an ensemble of CCSM4 historical runs (thin color lines with thick black being the ensemble mean) and in the CORE-II forced POP2 simulation (thick red line). Note that CCSM4 simulates a downward AMOC trend, while POP2 simulates an upward AMOC trend (Kim and Chang 2013).

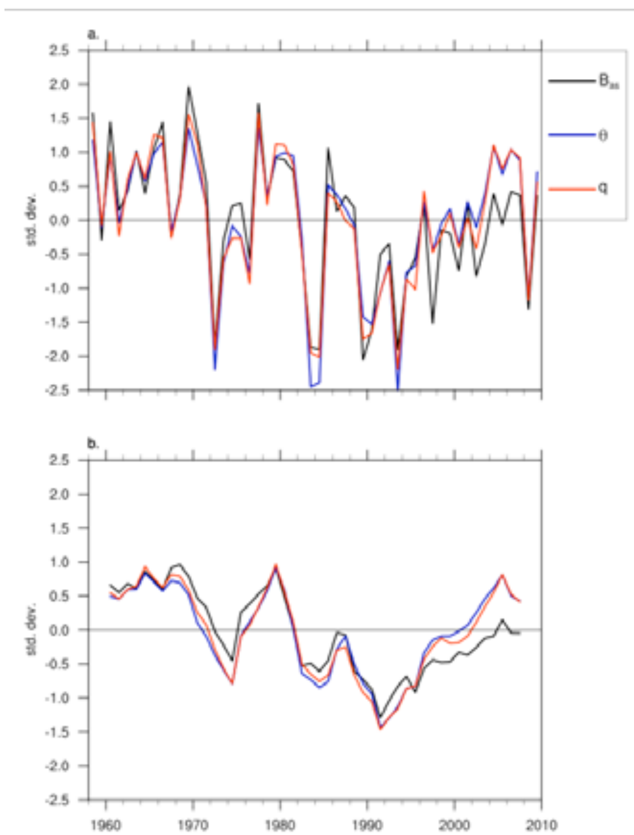

Figure 2. Anomaly time series of JFM-mean fields from CONTROL regionally-averaged over the Lab Sea Box region: (a) the 10m atmospheric potential temperature (θ) and specific humidity (q) together with the net surface buoyancy flux; (b) identical to (a), but after smoothing with running 5-year boxcar filter. All curves are normalized by the standard deviations of the respective unfiltered time series. The regional averages of θ and q are computed over the entire Lab Sea Box region (Yeager and Danabasoglu 2013).

Interactions between the Arctic Sea Ice Loss and the AMOC

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Rapid sea ice loss events (RILEs) are presented in nature and in climate models. Previous studies have suggested a role of ocean heat transport (OHT) (among other factors) in triggering RILEs. Arctic sea ice melting also induces changes in the freshwater export to the subpolar North Atlantic, which in turn perturb the AMOC and the associated OHT. The mechanisms and dominant timescales involved in the interactions between the Arctic sea ice and the AMOC are not well understood. The project proposes to study these processes in the NCAR CESM large ensemble runs.

Recent results

RILEs (following the definition in Holland et al. 2006) are presented in all CESM RCP8.5 ensemble runs (for years 2006-2080) that have been examined thus far. Arctic sea ice area in September is significantly correlated with the annual mean OHT into the Arctic, but the correlation decreases when the linear trend in both time series is removed. This suggests an important role of OHT on the downward trend of Arctic summer sea ice cover, but the interannual variability in the latter is additionally influenced by other factors.

Given that Greenland-Iceland-Norwegian (GIN) sea overflow is a key connection between the Arctic and the AMOC, the project examined the relationship between the overflow amplitude, defined here as the vertically integrated southward transport across the southern boundary of GIN Sea, and the AMOC (Figure 1). The overflow and local AMOC (maximum overturning streamfunction at 64°N) are highly correlated at zero lag (Figure 1a,b). On the other hand, the relationship between the subpolar and hemispheric AMOC is time-scale dependent. On time scales concerning the linear trend, subpolar AMOC change is linked to a basin scale AMOC response similar in spatial structure to the mean state AMOC (Figure 1c), which corresponds to the entire hemisphere's AMOC strengthening or weakening as a whole. When the linear trend is removed (with interannual variability remaining), the response becomes regional (Figure 1d), and strengthened overflow/subpolar AMOC is associated with stronger sinking north of 60°N and stronger deep southward flow beneath 3000m which extends to 40°N, but weakened surface convections around 55°N and weakened southward flow in the intermediate layers between 1500m and 3000m, and vice versa.

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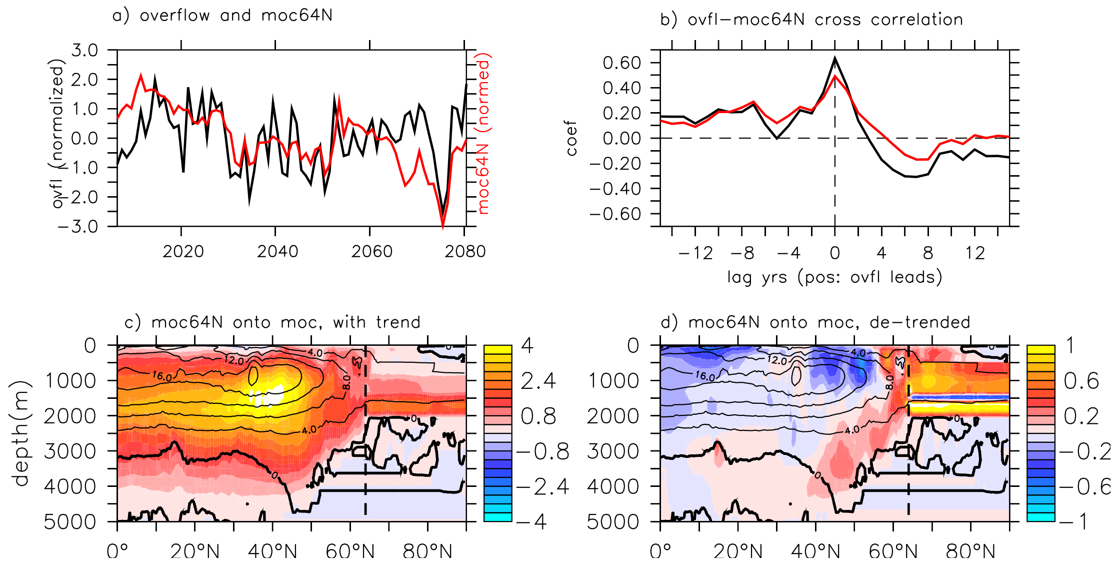

Figure 1. a) Normalized overflow amplitude (black) and the AMOC index at 64°N (red). b) Cross correlation between the overflow amplitude and AMOC index at 64°N, positive (negative) correlation means overflow leading (laging) the AMOC index. Black (red) line corresponds to full (de-trended) time series. c) Regression patterns between the AMOC index at 64°N and northern hemisphere AMOC (color shading), overlaid on long-term mean AMOC in the northern hemisphere (black contours). The vertical dashed line marks the 64°N latitude. d) Same as c) except now the linear trend in both the AMOC index at 64°N and hemispheric AMOC is removed. All computations used annual mean data.

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

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The aim of this project is to understand the sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) to changes in the calving rate of icebergs from the Greenland Ice Sheet (GrIS). The project is motivated by the fact that many climate prediction models do not simulate iceberg drift and melt, but instead (rather crudely) discharge runoff along the edge of the ice sheet. In reality, icebergs drift many thousands of kilometers from their source before finally melting. This project has developed a sophisticated, thermodynamic, iceberg model (MITberg) that is coupled to MITgcm (and planned for release in 2014). The model will be used to explore the sensitive of the AMOC to near-future increases in Greenland iceberg calving.

Recent results

The state-of-the-art thermodynamic iceberg model incorporates the most recent developments in iceberg physics, and when coupled to MITgcm (at 1/6° spatial resolution), produces realistic iceberg trajectories and melt rates. The project recently implemented a realistic calving scheme based on the annual discharge of ice from 34 regions of the GrIS (Rignot et al. 2008) (Figure 1). This leads to approximately 400km^3 of ice (~0.01 Sv) being calved annually to the ocean and large number of icebergs discharged from major ice streams such as Jokobshaven, Helheim, and Kangerlussuaq. The project is about to start three 50-year model simulations: a control run in which calving is kept at modern-day rates, and two perturbations experiment. The first increasing calving to supply a runoff flux of 0.05 Sv, and the second, rather extreme scenario, increasing calving rates to give a freshwater discharge of 0.1 Sv — an upper estimate of future increase in Greenland runoff. In each simulation, the response of the AMOC, subpolar gyre, and northward heat transport will be studied.

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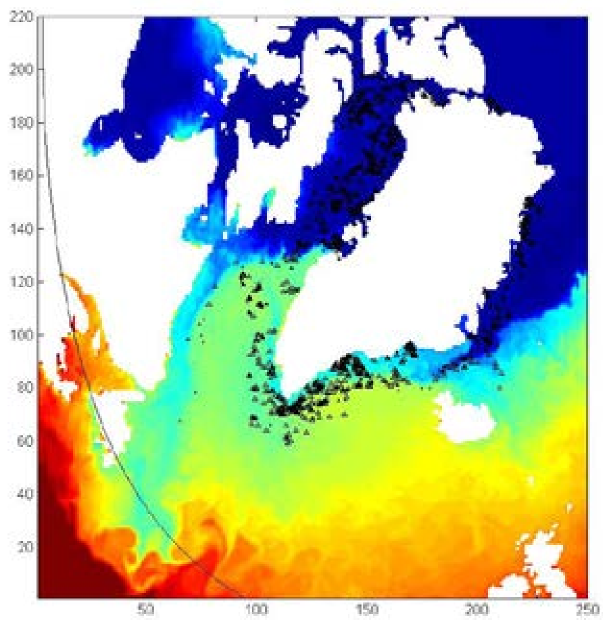

Figure 1. A snapshot of the size and distribution of icebergs (black triangles) seeded from 34 locations around the coast of Greenland. The calving locations and volume of ice discharged each year is based on the work of Rignot et al. (2008), and assumes ~400km^3 of ice is calved annually from the ice sheet. The model is being validated by comparing the number of icebergs that drift south of 48°N (latitude line drawn at 48°N) to historical observations from Newfoundland in this region that begin in the early 1900s. The iceberg model (MITberg) is coupled to MITgcm ocean—sea ice model integrated at 1/6°. The ocean colors (blue to red) show model sea-surface temperature.

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

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This project has explored the anatomy of the buoyancy gain part of AMOC – an Abyssal Upwelling Cell (AUC) – that transforms the densest waters in the Atlantic (AABW and the Nordic Seas Overflows) into warmer, lighter density classes (NADW), which are subsequently exported across the equator via the DWBC. The field experiment (including a moored array of profilers and a microstructure survey) focused on quantifying the strength and structure of diapycnal mixing along the MAR and deep Gulf Stream and the interior flows of LNADW through the western basin that result from that mixing.

Recent results

- The AUC's upward transfer of mass and buoyancy gain is remarkable for its amplitude. The gain of 1-2 Sv of AABW flowing northward across the equator is inflated, through entrainment of overlying LNADW, to approximately 8 Sv at depths greater than 4800 meters by the time it reaches 16°N. In the basins to the north, that volume of cold water subsequently upwells across the 1.8° isotherm and is returned to the South Atlantic as NADW at depths between 2500-4000 m.
- DynAMITE has confirmed that the AUC is primarily driven by diapycnal mixing along the MAR between latitudes 10°- 40°N. Below the crest of the MAR, entrainment of overlying waters warms the bottom layers in the direction of the basin-scale circulation, and vortex stretching enhances the northward penetration of AABW properties. As topography steepens on the MAR, competition between topographic Rossby waves and planetary Rossby waves causes the diapycnal flows to veer uphill and then turn westward into the interior basin. These interior flows join the DWBC near Blake Bahama Ridge, boosting its transport by 10-15 Sv. Mixing weakens the stratification creating massive reservoirs of low potential vorticity waters – an abyssal analog to water masses formed by deep convection and buoyancy loss at high latitudes in the MOC.
- Supplementing the field measurements acquired by this program, analyses of basin-scale PV distributions from climatology (HydroBase3) have provided a framework for describing the structure of the AUC and a roadmap for the interior flows. One of DynAMITE's central results is an updated view of the buoyancy-forced, interior circulation beneath the thermocline (Figure 1). It emphasizes the importance of turbulent mixing and the mid-ocean ridges in the buoyancy gain portion of the AMOC, and for setting the deep interior layers in motion. Chemical tracers (e.g. dissolved oxygen, CFCs, SF_6) from repeated hydrographic sections (e.g., A20, A22, RAPID, Line W) strongly confirm this updated picture.
- The interior flows along the SE flank of Bermuda Rise appear to be similar in strength and amplitude to the DWBC flows measured through Line W, with sustained speeds of 10-30 cm/sec recorded at two moorings between the 4000 - 5000 meter isobaths. The deep isotherms between 1.65 – 1.8°C are vertically displaced by > 500 m during these high flow events. The interior transports are still being assembled from the moored data.
- Vertical diffusivities are intensified along the MAR and (we postulate) in the vicinity of the New England Seamounts where relatively high stratification and strong currents enhance wave/topography interactions.
- The AUC in the western North Atlantic differs fundamentally from that in the Brazil Basin where offset fractures convey dense waters toward the MAR crest and supply the mass required for upwelling. A significant portion of the mean circulation there occurs in canyons below the topographic

peaks. Such conduits are largely absent in the DynAMITE study region. In this basin, turbulent mixing results in vortex stretching such that beta dynamics govern the mean circulation and supply the mass required for net upwelling and buoyancy gain.

- The AUC accounts for the observed disconnect between AMOC variability measured at mid-latitudes (Line W, Labrador Sea) and the tropics (RAPID, MOVE) – at least for layers below the crest of the MAR. It further implies that on climate timescales, LNADW can be produced in, and exported from, the western North Atlantic in the absence of significant contributions from the Nordic Seas overflows.

Online data

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

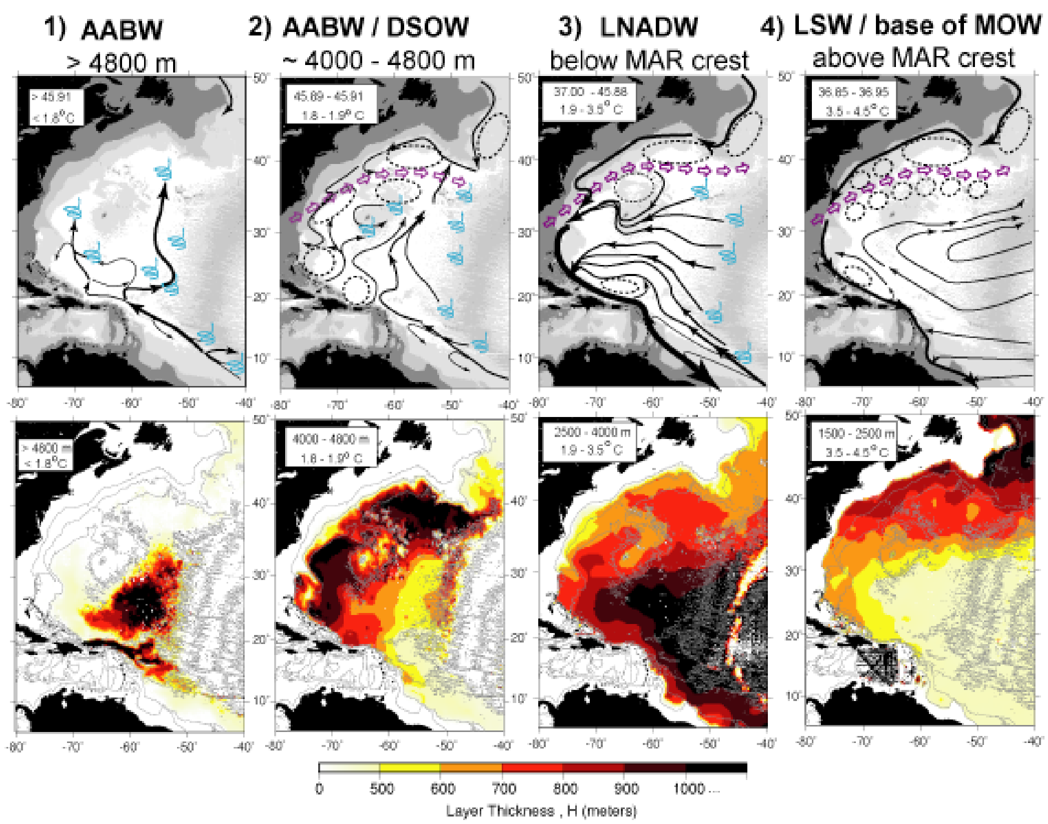

Figure 1. *Top row*: Schematic diagrams of the mean geostrophic interior flows (solid lines, arrows), recirculations adjacent to boundary currents (dashed ovals), and regions of locally enhanced diapycnal mixing (blue spirals) in 4 layers spanning depths > 1500 m. Purple arrows depict the mean location of the deep Gulf Stream. Potential density bounds, temperature and approximate depth ranges for each layer are labeled. Each layer corresponds to a generalized water mass class: AABW: Antarctic Bottom Water; AABW / DSOW: mixture of AABW and Denmark Strait Overflow Waters; LNADW: mixture of Nordic Seas Overflows and interior waters (upwelled AABW); LSW / MOW: Labrador Sea Water and base of the Mediterranean Outflow Waters. *Bottom row:* vertical thickness of each layer. Thickness maxima correspond to regions of locally enhanced diapycnal mixing: i) over rugged topography of the MAR (Layers 1-3), ii) in the deep Gulf Stream (Layer 2), and iii) in the waters formed by convective mixing in the Labrador Sea (Layer 4).

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

PIs: G. Danabasoglu[1] and J. Tribbia[1]
Collaborators: S. Yeager[1] and A. Karspeck[1]
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The overarching goal of this collaborative effort between NCAR, GFDL, and MIT was to advance the 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. Highlighted here are some recent results from the NCAR group obtained during the no-cost extension period.

Recent results

The project analyzed simulation characteristics from eighteen global ocean—sea ice coupled models with a focus on the mean AMOC and other related fields in the North Atlantic in Danabasoglu et al. (2013). These experiments use inter-annually varying atmospheric forcing datasets for the 60-year period from 1948 to 2007 and are performed as contributions to the second phase of the Coordinated Ocean-ice Reference Experiments (CORE-II). Despite using the same atmospheric forcing, the solutions show significant differences (Figure 1 shows an example of differences in AMOC). As most models also differ from available observations, the project identified biases in upper-ocean potential temperature and salinity distributions, mixed layer depths, and sea ice cover in the Labrador Sea region as contributors to differences in AMOC. These differences in the solutions do not suggest an obvious grouping of the models based on their ocean model lineage, their vertical coordinate representations, or surface salinity restoring strengths. Thus, the project attributes the solution differences among the models primarily to use of different subgrid scale parameterizations and parameter choices as well as to differences in horizontal and vertical grid resolutions in the ocean models. Use of a wide variety of sea ice models also contributes to these differences.
Much of the work on historical AMOC mechanisms is detailed in Yeager (2013), which includes a novel analysis of the large-scale circulation response to wind- and buoyancy-forcing perturbations in terms of time-dependent vorticity balances. The findings underscore the significant dynamical effects of abyssal flow over bathymetry, and they greatly clarify the overturning and gyre dynamics that underpin AMOC and Atlantic Multi-decadal Variability in our ocean model simulations. Work is ongoing to explore the major ramifications of these results for evaluating model behavior and fidelity and for interpreting observed inter-annual variability signals at the RAPID array latitude.

Yeager (2013) additionally explores the mechanisms associated with sea surface temperature (SST) variability in the North Atlantic, using observation-based reconstructions of the historical surface states of the atmosphere and ocean as well as simulations run with the Community Earth System Model version 1 (CESM1). The relationship between air-sea heat flux and SST during 1948-2007 yields evidence of a positive heat flux feedback at work in the subpolar gyre region on quasi-decadal timescales. Warming of the high latitude Atlantic precedes an atmospheric response, which resembles a negative North Atlantic Oscillation (NAO) state. The historical flux dataset used to estimate temporal variations in North Atlantic deep-water formation suggest that NAO variations drove strong decadal changes in thermohaline circulation strength in the last half century. Model simulations corroborate the observation-based inferences that substantial changes in the strength of AMOC ensued as a result of NAO-driven water mass perturbations, and that changes in the large-scale ocean circulation played a significant role in modulating North Atlantic SSTs.

Also completed was the evaluation of a 48-member ensemble adjustment Kalman filter (EaKF) for the CESM1 ocean component (Karspeck et al. 2013). The ocean assimilation system was developed to support the generation of historical ocean-state estimates and ocean-initialized climate predictions with CESM. In this initial configuration of the system, daily subsurface temperature and salinity data from the 2009 World Ocean Database are assimilated into the ocean model from January 1, 1998 to December 21, 2005. Each ensemble member of the ocean is forced by a member of an independently generated CESM atmospheric EaKF analysis, making this a loosely-coupled framework. Over most of the globe, the time-mean temperature and salinity fields are improved relative to an identically forced ocean model simulation without assimilation. This improvement is especially notable in strong frontal regions such as the western and eastern boundary currents. The assimilation system is most effective in the upper 1000 m of the ocean, where the vast majority of in situ observations are located. The project identified several challenges in assimilating real observations that arise from using an ocean model with strong regional biases, coarse resolution, and low internal variability.

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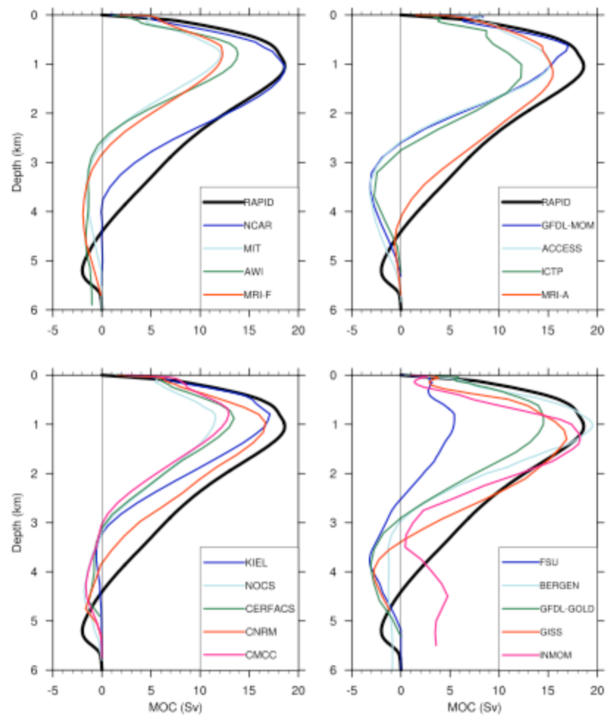

Figure 1. Years 2004 - 2007 mean AMOC depth profiles at 26.5°N from the eighteen models participating in the CORE-II project. The model solutions are presented in comparison with the 4-year mean (April 2004 - March 2008) RAPID data (thick black lines plotted in each panel).

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

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This is a new, highly collaborative project between GFDL, NCAR, and WHOI aimed at advancing our understanding of simulated AMOC variability, the impact of that variability on the atmosphere and climate, and the relevance of that variability to our ability to make decadal climate predictions. The study is motivated by the role that AMOC is thought to play in decadal climate variability and prediction, and by the critical need to improve our understanding of mechanisms and assessing the fidelity and robustness of simulated AMOC variability against limited observations. A major facet of this project is the synergy achieved through the coordinated efforts between the three institutions involved. In particular, the development of common metrics and the coordinated design and analysis of focused, sensitivity experiments using suites of models from NCAR and GFDL, and WHOI's contribution in analysis of mechanisms and climate impacts are critical aspects of our work. The specific goals include investigating impacts of model resolution, parameterizations, biases, and mean states on AMOC variability; determining the impact of ocean eddies on simulated AMOC and its variability; investigating AMOC variability and mechanisms in the recent past; improving our understanding of how particular physical processes and climate state information may give rise to predictive skill related to AMOC variability; and evaluating how model differences in simulating AMOC variability affect related decadal predictability. At all three institutions, work has just begun towards accomplishing these goals.

Recent results

At NCAR, to investigate the sensitivity of AMOC variability to model biases in the North Atlantic associated with the incorrect path of the North Atlantic Current (NAC), the project has started preliminary work to further refine an adiabatic technique to partly correct the NAC path. These exploratory simulations have been done using forced ocean simulations. The project is about to start a multi-century fully-coupled simulation with this correction. This experiment complements the completed simulations where it explores the sensitivity of AMOC variability to model resolution and ocean model parameterizations. The early results from these experiments show substantial differences in AMOC variability among these simulations.

The initial efforts at GFDL have focused on several fronts. First is the initial diagnosis and evaluation of AMOC variability in a suite of new, coupled models. It find that the characteristics of AMOC variability can vary greatly in response to many aspects of model formulation, including resolution and physics choices – consistent with the findings at NCAR. This sensitivity presents a major challenge to obtaining a more robust understanding of the mechanisms of AMOC decadal variability. The second focus has been the design and execution of numerical experiments that evaluate the response of the coupled system to synthetically generated surface flux forcing, such as that generated by the North Atlantic Oscillation (NAO). These suites of experiments, to be conducted with both GFDL and NCAR climate models, will provide a framework for evaluating how different coupled climate models respond to a common pattern of atmospheric flux forcing that appears to be important for AMOC variability. The transient and longer-term response to the forcing will illuminate the inherent adjustment processes of the models that may play an important role for internal decadal variability of the AMOC and the associated decadal predictability. A series of experiments is planned in which aspects of the flux forcing will be varied, including its temporal structure, in order to better clarify the climate system response to the NAO and its role in AMOC variability.

At WHOI, analysis of the Community Earth System Model version 3 (CCSM3) present-day control simulation continued both as a no-cost extension of the previous NOAA CPO project (Kwon, Frankignoul, and Danabasoglu; expired in July 2013) and as part of the current proposal. In Frankignoul et al. (2013), they examined the impact of AMOC variability on the atmospheric circulation in CCSM3. In the last 250 years of the integration, a positive NAO is found to drive the stronger AMOC, and also a positive NAO-like atmospheric response to the strengthened AMOC is detected. The latter implies a weak positive feedback through the atmosphere-ocean coupling between the AMOC and NAO. Also extended was the earlier work on the strong 20-year AMOC variability in CCSM3 to include an analysis of AMOC in density space – in addition to AMOC in depth space. This new analysis, detailed in Kwon and Frankignoul (2013), sheds light on latitudinal differences in the structure and variability of AMOC.

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

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In this new interdisciplinary collaborative project, the project seeks to i) produce an improved and reliable decadal prediction (DP) system within the Community Earth System Model (CESM) framework, including predictive capabilities for marine ecosystems and biogeochemical constituents, and ii) advance the use of DP simulations in regional and societal impact studies. Attainment of these goals and developing a well-founded DP system relies on improved understanding and technical capabilities in four fundamental areas: (1) improving the understanding of intrinsic decadal variability and mechanisms; (2) evaluating the inherent predictability constraints of forecast models; (3) evaluating practical forecast system design methods; and (4) generating capabilities for incorporating fully-coupled data assimilation and ocean ecosystems and biogeochemistry into the DP system. These four topics form the foundation of the project. At all three institutions, work has progressed towards accomplishing the goals. A brief summary of the recent work is provided below.

Recent results

The project has started a systematic assessment of the sensitivity of the AMOC variability in CESM to model resolution and ocean model physics at NCAR. For the former, two 1500-year preindustrial-coupled control integrations are now complete. These cases differ only in the horizontal resolution of their atmospheric component (1° vs. 2°). For the latter, several 600-year simulations have been performed where we changed some poorly constrained ocean model parameters with high impacts on model solutions – determined based on previous studies. These sensitivity experiments include modifications in the parameterizations of submesoscale mixing, mesoscale mixing, horizontal viscosity, and vertical mixing. Preliminary analyses show substantial differences in AMOC variability among these integrations, but there are some robust features as well, e.g., Labrador Sea boundary layer deepening leads AMOC maximum and AMOC maximum leads enhanced Nordic Sea overflow transports.

The predictability properties of AMOC have been measured and compared to the predictability of upper 500 m heat content in the North Atlantic based on control simulations from nine comprehensive coupled climate models in Branstator and Teng (2013). What was found is that, on average, AMOC is less predictable than heat content for generic annual mean fluctuations (i.e., AMOC uncertainty grows more rapidly than heat content uncertainty as shown in Figure 1), but is more predictable than heat content for 5- and 10-year averages. Also, there are spatial patterns of AMOC that have especially high predictability. These patterns are associated with heat content fluctuations with above average predictability, so it may be that AMOC is a positive influence on the predictability of heat content for these special structures.

The project has assessed retrospective DP skill of sea surface temperature (SST) variability in the existing initialized climate prediction experiments with CESM (Karspeck et al. 2013). It evaluated ensemble forecasts initialized with two different historical ocean and sea ice initial conditions and compared to an ensemble of uninitialized coupled simulations. Both experiments are subject to identical twentieth century historical radiative forcings. Each initialized forecast consists of a 10-member ensemble integrated over a 10-year period. One set of historical ocean and sea ice conditions used for initialization comes from a forced ocean-ice simulation driven by the Coordinated Ocean-ice Reference Experiments inter-annually varying atmospheric dataset (CORE-II). Following the Coordinated Model Inter-comparison Project phase 5 (CMIP5) protocol, these forecasts are initialized every five years from 1961-1996, and every year from 2000-2006. A second set of initial conditions comes from historical ocean state estimates obtained through the assimilation of in situ temperature and salinity data into the CESM ocean model. These forecasts are only available over a limited subset of the CMIP5 recommended start dates. Using a probabilistic measure of the correlation coefficient skill score, we have found that both methods result in retrospective SST prediction skill over broad regions of the Indian Ocean, western Pacific Ocean, Southern Ocean, and North Atlantic Ocean that are better than reference skill levels from a spatio-temporal auto-regressive statistical model of SST (at a 90% confidence level). However the subpolar gyre region of the North Atlantic stands out as the only region where the CESM skill in predicting SST variations is better than the statistical reference forecasts and able to outperform uninitialized simulations (Figure 2).

Several shortcomings have been addressed of the existing data assimilation system. The project has implemented a new method for initializing the ensemble filter, tested for appropriate localization, specified more realistic estimates of representativeness error, and applied adaptive inflation algorithms. When applied in short-term data assimilation experiments, these changes suggest that the system will be more accurate and reliable over the long term. The project has also completed the infrastructure developments needed for the CESM – DART (Data Assimilation Research Testbed) multi-component coupled data assimilation framework.

At WHOI, influence of the AMOC variability on the atmospheric circulation is investigated from a 700-year segment of the Community Climate System Model version 4 (CCSM4) preindustrial control simulation. The AMOC variability, which is largely driven by the North Atlantic Oscillation (NAO), significantly influences the atmosphere during winter. The winter response to an AMOC intensification at 30°N has some similarity with a negative phase of the NAO, and it is best seen after a delay of six to nine years when the SST footprint of the AMOC shows a strong warming in the subpolar gyre and a weaker cooling in the subtropical gyre, resembling the observed Atlantic Multi-decadal Variability pattern. The links to the air-sea interactions at the seasonal scale and their comparison with the observations suggest that the air-sea coupling in the cold season is more realistic in CCSM4 than in previous versions of CCSM3. A paper reporting this result is in preparation.

At Stony Brook, two efforts have been completed. The first is aimed at investigating the impacts of large-scale SST anomalies on wintertime cyclones (December to March) in the eastern US with the Community Atmosphere Model version 5 (CAM5) and the second involves its downscaling simulation using the Weather Research and Forecasting (WRF) model. In order to establish an observational basis, the project first diagnosed the cyclone statistics for each year, including the number and track of different intensity category, using reanalysis products. What was found is that these statistics differ greatly for different years, setting a target for DP. Secondly, the same statistics were calculated in the 1° resolution version of CAM5 forced by observed SSTs. Findings indicate that CAM5 captured the statistics of intermediate and weak cyclones, but it missed many deep cyclones. The WRF at 20 km resolution that is laterally forced by CAM5 is able to better simulate deep cyclones, but the number is more than in observations. WRF results are also found to be moderately sensitive to its physical parameterization configurations. We are getting ready to use observed decadal variations of SST and results from the DP experiments to force the CAM5 and WRF and investigate how the decadal variability of cyclone statistics can be attributed and predicted.

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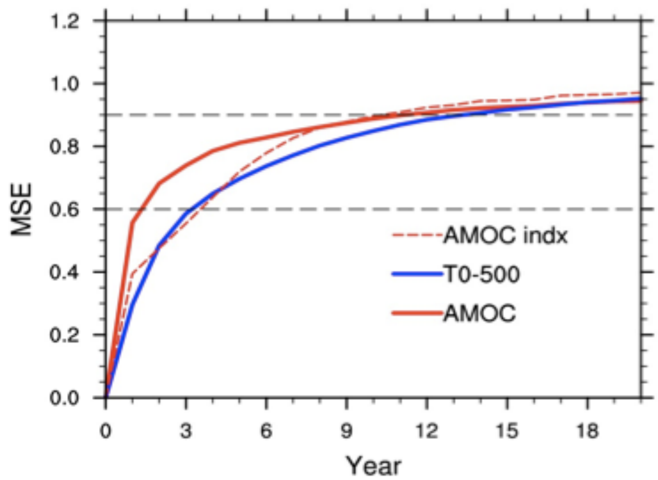

Figure 1. Solid lines are the mean spread of upper 500 m North Atlantic heat content (blue) and AMOC (red) for PC1-10 in perfect model initial perturbation experiments divided by the spread of states in control integrations. Presented are the average of such ratios as a function of forecast range for 9 CMIP5 class models. The dashed line is similar but for a conventional scalar AMOC index.

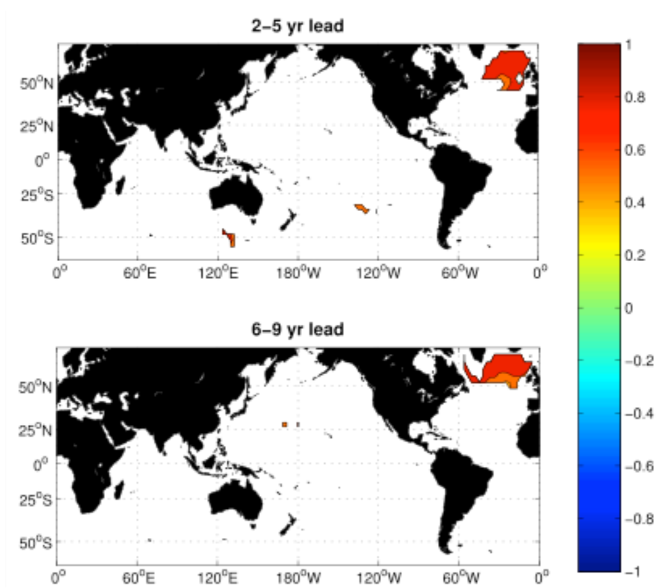

Figure 2. Average of SST correlation coefficient distributions for the hindcast-initialized forecasts (evaluated for start-dates from 1961-2005). Only those correlation scores that exceed chance at the 90% confidence level and exceed the skill of the uninitialized run at a 90% confidence level are plotted.

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

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The objective of this program is to study the circulation in the Iceland Sea at the depth of the Denmark Strait sill. In July 2013 a total of 25 RAFOS floats were deployed in the Iceland Sea, along with six sound sources to tracks the floats. Half of the floats are programmed for one-year mission and will surface in May 2014, the other half are programmed for two-year missions. Another 40 floats will be deployed in July 2014. These will be programmed for one-year missions.

Recent results

One test float, programmed to surface in February 2014, relayed its data back to shore. The data indicates that nearly all sound sources are working properly. One sound source seems to have a clock problem and will be replaced by a different sound source during the 2014 deployment cruise.

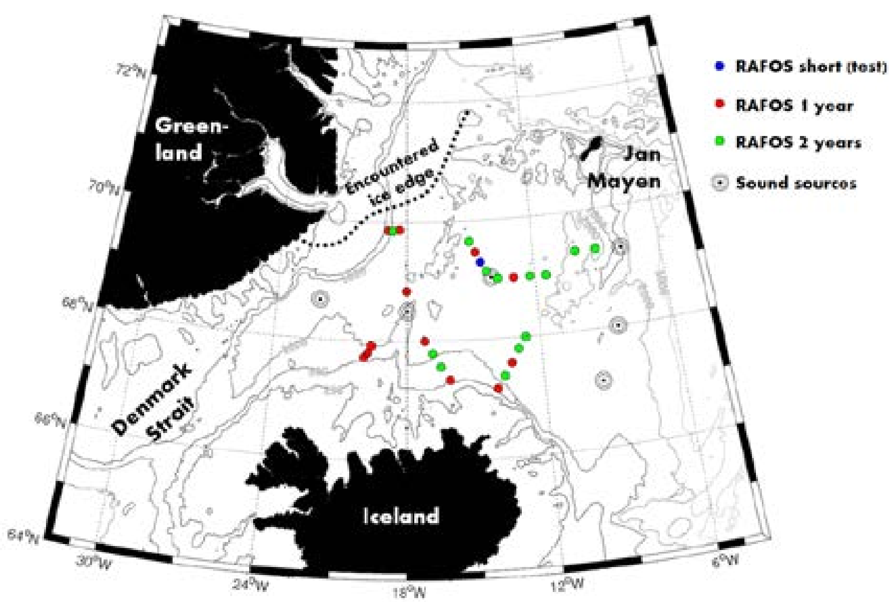

Figure 1. Deployment positions of RAFOS floats and sound sources deployed in the Iceland Sea in July 2013. Red (Green) circles are floats programmed to surface in May 2014 (2015). The blue test float surfaced in February 2014.

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

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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), the project 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). The MHT variability is significantly correlated with the AMOC, where a 1 Sv increase in the AMOC would yield a 0.05 ± 0.01 PW increase in the MHT. Detailed analysis of transport estimates from AX18 (Dong et al. 2009, 2011) identified differences between model simulations and observations in a variety of aspects.

Monthly climatology of temperature and salinity from observations and numerical models are used to estimate the Atlantic Meridional Overturning Circulation (AMOC) at 34°S. The main goal of this study is to better understand the model-data differences in the AMOC seasonal variations. Observational estimates suggest that the geostrophic transport plays an equal role as the Ekman transport in the AMOC seasonal variations, whereas in the models the Ekman transport controls the AMOC seasonality (Figure 1). Model biases in both the geostrophic and Ekman transports contribute to this difference. Compared to observations, models show stronger amplitude of seasonal cycle in the Ekman transport and weaker amplitude in the geostrophic transport. The strong seasonality in the Ekman transport is directly linked to the strong seasonal variations of zonal wind stress in the models. The strong seasonal cycle in the geostrophic transport from observations is contributed by the vertical coherence in the velocity (Figure 2), whereas the models show strong baroclinicity below the surface mixed-layer. This baroclinicity is probably due to the strong vertical stratification in the models, which prohibits vertical propagation of signals.

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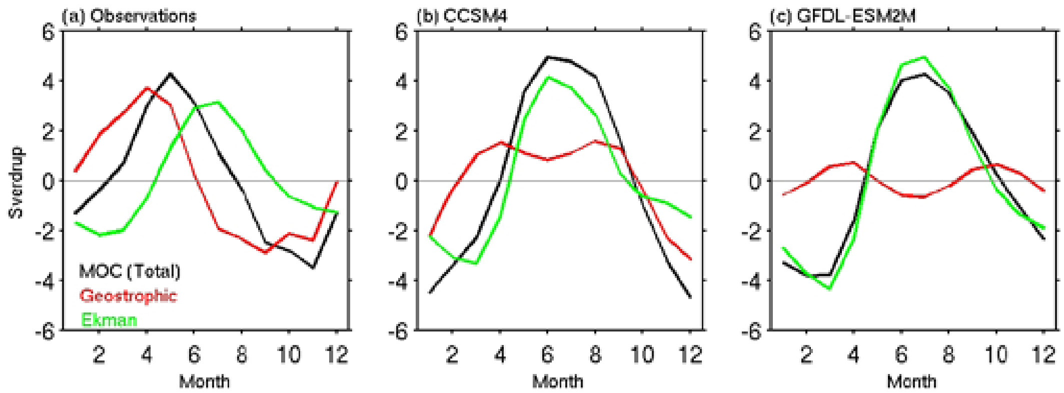

Figure 1. Seasonal variations of the AMOC at 34°S (black) and contributions from the geostrophic (red) and Ekman (green) components estimated from (a) observations and two CIMP5 models (b) CCSM4 and (c) GFDL-EMS2M. The mean values from AMOC and each component have been removed.

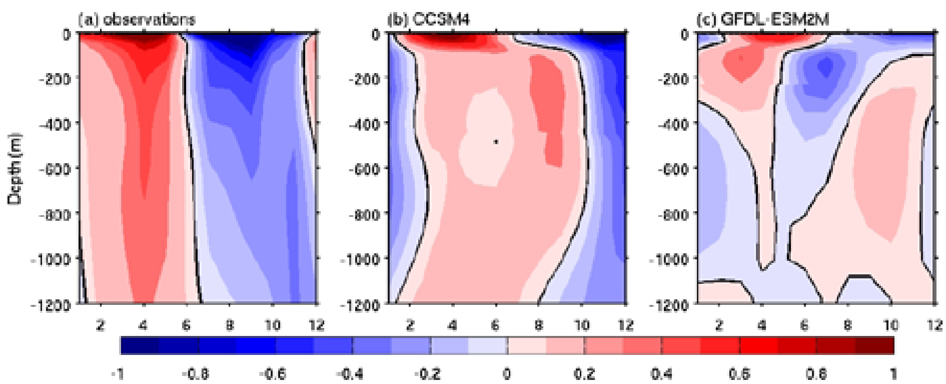

Figure 2. Month and depth distribution of zonally averaged meridional velocity along 34°S in the upper ocean computed from (a) observations and two CMIP5 models (b) CCSM4 and (c) GFDL-EMS2M. Time-mean values at each depth have been removed to better demonstrate the seasonal variations. Unit is 10^{-3} m/s.

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

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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. Data continues to be delivered via the Oleander web site and have included several downloadable files of Gulf Stream North Wall position and upper ocean fluxes along the Oleander line.

The 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, the 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; and 4) to investigate the linkages between these oceanographic regimes and their connections to large-scale forcing fields.

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

A detailed comparison between Oleander-derived sea surface height and the AVISO sea surface height products show excellent agreement between the two systems. The ADCP complements altimetry well in that it provides detail about the velocity field at scales as small as a few kilometers, and can measure currents and transports accurately over distances of a few 100 km. The Oleander route spans three distinct deep-sea regions: the Slope Sea, the Gulf Stream, and Sargasso Sea. Agreement in sea surface height variability depends principally upon the length of the section being compared, and not upon eddy kinetic energy levels. For example, yearly averages for short subsections (quiet Slope Sea and energetic Gulf Stream) have correlation coefficients in excess of 0.9, whereas across the longer Sargasso Sea section the correlation drops to 0.64. On large scales velocity uncertainties accrue leading to increasing large flux errors.

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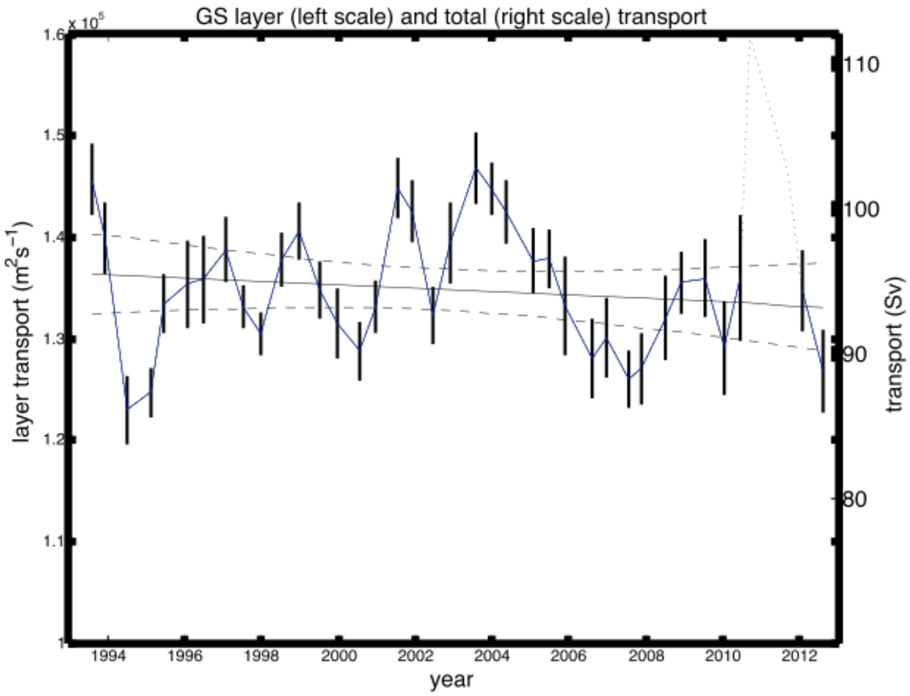

Figure 1. Annually averaged Gulf Stream surface layer flux (termed 'layer transport') stepped every half-year. The mean = (1.34 ± 0.6) x 10^5 m^2s^{-1}. The slope of the line = -173 ± 377 $m^2 s^{-1} yr^{-1}$, equivalent to a decrease in sea level difference of 1.5 ± 3.3 mm yr^{-1} or 0.03 m over the 20 year observing period. The dashed lines indicate the 95% confidence limits of the linear fit. Note the large ~8% extrema around 1994, 2003, 2007, and 2012. The right axis shows 0 - 2000 m transport assuming a scale factor of 700. The dotted line in 2011 reflects a scarcity of data due to an extended dry dock period and instrument difficulties after the dry dock period. The Gulf Stream is the region of flow parallel to the maximum velocity vector between the zero crossings on either side of the maximum (Rossby et al. 2014).

An Interactive Multi-Model for Consensus on Climate Change

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

Another aspect of synchronization in climate is the synchronization of climate modes. These modes represent low-order subsystems in climate and it has been shown that they often synchronize. An important element in the theory of synchronization between coupled nonlinear oscillators is coupling strength. The theory of synchronized chaos (Pecora et al. 1997, Boccaletti et al. 2002) predicts that in many cases when such systems synchronize, an increase in coupling strength between the oscillators may destroy the synchronous state and alter the system's behavior. These ideas were initially explored in a network of four climate oscillators, namely El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the North Pacific Index (NPI), and the Pacific Decadal Oscillation (PDO) (Tsonis et al. 2007, Swanson and Tsonis 2009, Wang et al. 2009). The results indicate that this network in the 20th century synchronized several times. It was then found that in those cases where the synchronous state was followed by a steady increase in the coupling strength between the indices, the synchronous state was destroyed, after which a new climate state emerged. These shifts are associated with significant changes in global temperature trend over decadal time scales. There is evidence for such type of behavior in three climate simulations (control and CO2 forced) using simulation from state-of-the-art models.

Recent results

Part of the project goal is to understand relationships between regime shifts and synchronization in a set of ordinary differential equations (ODE's) representing climate modes. To this end, synchronizations were further studied by extending the previous analysis to include more indices. Some results are shown in Figure 1. The main conclusion here is that de-synchronization does not always mean a regime shift. For example, while in the early 1940s a climate shift took place, no shift occurred in the 1920s or early 1930s. In accordance with the previous results, only in those times when increase in coupling is involved de-synchronization is associated with a climate regime. In relation to the goals of the complete proposal, it is important to establish the mechanism via which synchronization and coupling increase occur. The results also indicate that in the four mode network the direction of influences (Figure 2) begins with North Atlantic coupling to North Pacific which then couples to tropical Pacific which in turn couples back to North Atlantic (Wang et al. 2009, Ineson and Scaife 2009).

The project is now in the process of evaluating all possible candidate models. This is a straightforward procedure that will be completed by the end of the second year of funding. Once the project is finished with this evaluation, the project will then proceed (in the third and final year) to study synchronization and coupling between the modes in the derived set of ODEs and its relation to global temperature prediction and shifts.

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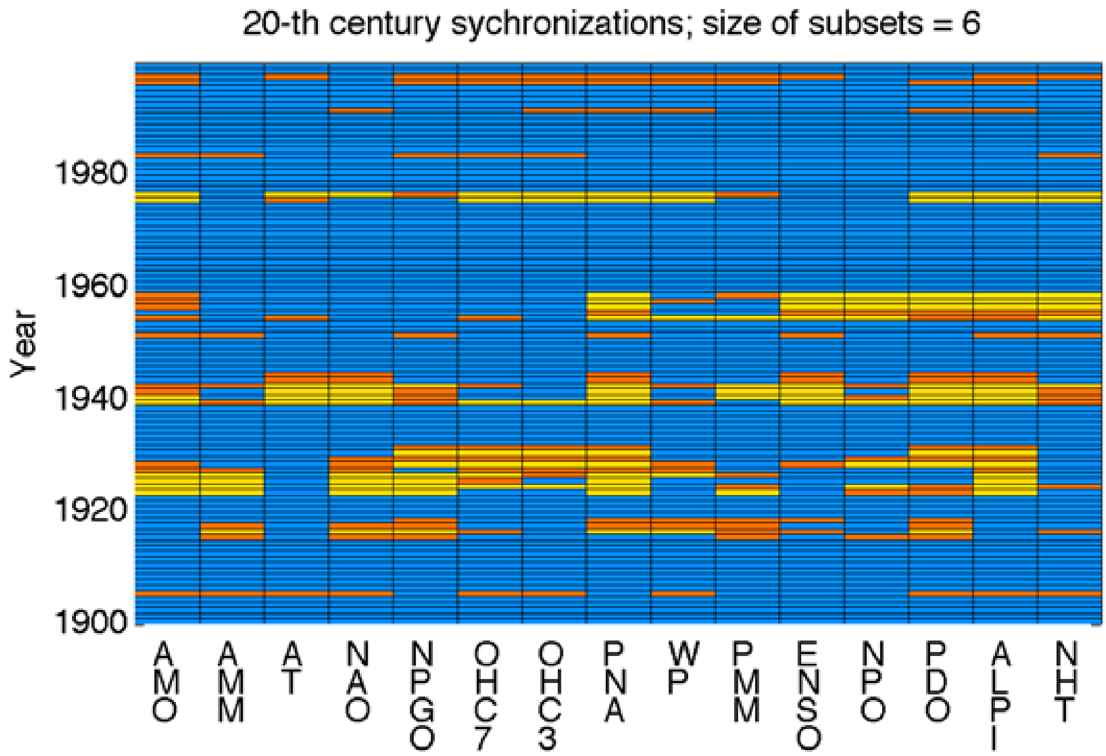

Figure 1. On the x-axis are the different modes and on the y-axis is time. This figure may be interpreted as follows. Horizontal orange or yellow lines indicate synchronization events and the modes involved in each synchronization event. AMO: Atlantic Multi-decadal Oscillation, AMM: Atlantic Meridional Mode, AT: Atmospheric-mass Transfer anomalies index, NAO: North Atlantic Oscillation, NPGO: North Pacific Gyre Oscillation, OHC7: Ocean Heat Content at 700 meters index OHC3: Ocean Heat Content at 300 meters index, PNA: Pacific North America index, WP: Western Pacific Pattern index, PMM: Pacific Meridional Mode, ENSO: El Nino/Southern Oscillation 3.4, NPO: North Pacific Oscillation, PDO: Pacific Decadal Oscillation, ALPI: Aleutian Low Pressure index, NHT: Northern Hemisphere Temperature.

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, the study can assess the sensitivity of this circulation to perturbations and explore the possibility of rapid changes in the system (Sevellec and Fedorov 2014a,b). In addition, it 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 (Sevellec and Fedorov 2013a). Finally, the project can study how initial temperature and salinity perturbations affect other characteristics of the ocean on decadal timescales (including upper-ocean-temperature and poleward heat transport).

Recent results

One of the main results of this year concerns the importance of the deep ocean for decadal climate prediction. In fact, assessing the limits of oceanic decadal predictability is critical for making progress in climate prediction. However, even when forced with the observed surface fluxes, ocean general circulation models develop biases in temperature and salinity fields. Typically, these biases amplify in coupled models. In the present study, two complimentary questions are asked related both to decadal prediction and the problem of model bias. First, can we temporarily reduce the bias and potentially improve prediction by slightly perturbing the initial conditions used for model initialization? Second, how much would such initial perturbations grow? To answer these questions, the project will conduct an optimization analysis of a realistic ocean GCM and compute optimal perturbations in temperature and salinity that can reduce the model bias most efficiently during a given time interval. Findings suggest that in order to reduce this bias, especially pronounced near the ocean surface, initial perturbations should be imposed in the deep ocean (specifically in the Southern Ocean). On decadal timescales, a 0.1°C perturbation in the deep ocean can induce a temperature anomaly on the order of several degrees in the upper ocean, partially reducing the bias - transient growth of such perturbations peaks after about 14 years.

A corollary of these results is that very small errors in model initialization in the deep ocean can produce large errors in the upper-ocean temperature after a decade or two of numerical simulations, which can be interpreted as a decadal predictability barrier associated with ocean dynamics. The physical mechanism of the error growth includes the excitation of large-scale quasi-stationary waves (or eddies) in the Southern Ocean. It shows that a strong meridional temperature gradient in this region enhances the sensitivity of the upper ocean to deep-ocean perturbations through non-normal dynamics facilitating the generation of these waves. Ultimately, the results emphasize the crucial role of the deep ocean (Figure 1), and the Southern Ocean in general, for decadal climate prediction (Sevellec and Fedorov 2013b).

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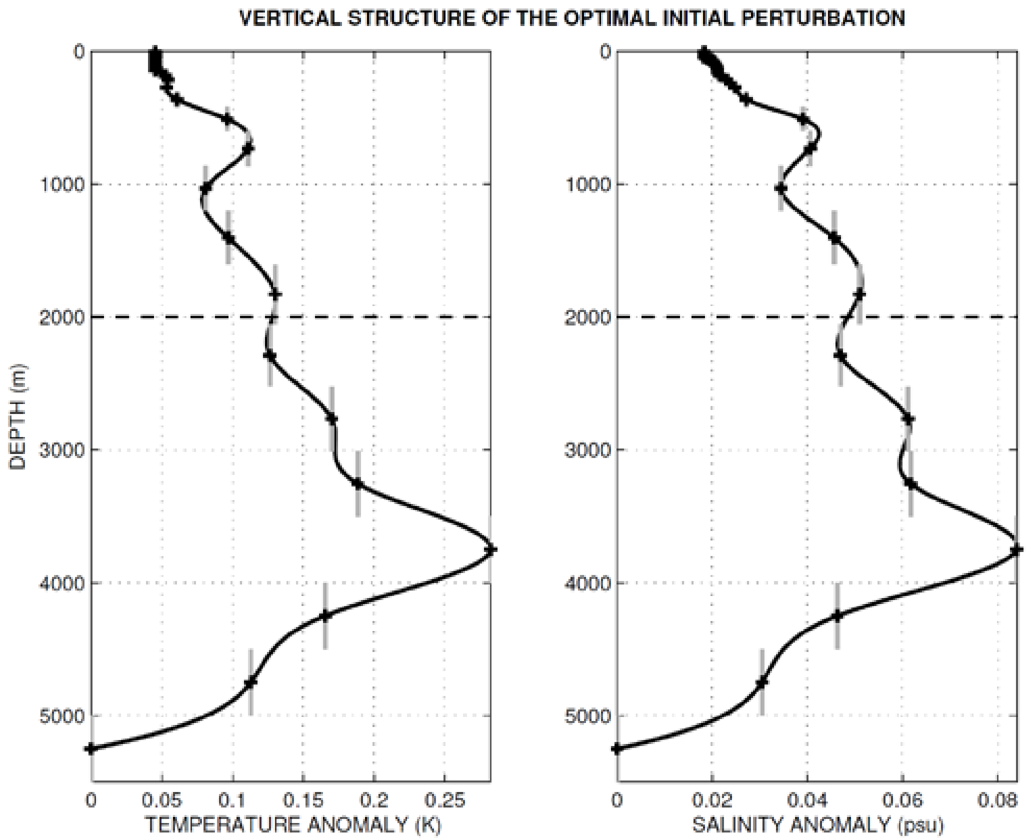

Figure 1. In effect, the plot shows the sensitivity of the upper ocean temperature to disturbances at different depths in the study of Sevellec and Fedorov (2013b). The largest sensitivity is found at 3700m. The model data are shown as crosses connected with a black solid line (cubic spline interpolation). Short grey vertical lines indicate the thickness of each level in the ocean GCM; a horizontal dashed line indicates the typical depth limit of ARGO floats (2,000 m).

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

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In the Southern Ocean, meridional overturning in the Pacific is analogous to meridional overturning in the Atlantic, and the same methods can be used to study both. The objectives of this project have focused on characterizing meridional heat transport in the Pacific Ocean basin, because the most rapid melting of the Antarctic continent has been reported in the southeastern Pacific Ocean, in West Antarctica, and particularly in the Amundsen Sea Embayment near Pine Island Glacier. The project's 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. The study uses a combination of historical data, profiling Argo floats, satellite data, and modeling tools to evaluate oceanic heat transport and storage through the Pacific and in the high-latitude Southern Ocean.

Recent results

- Meridional overturning circulation at 32°S in the Pacific has been evaluated from a combination of Argo floats, reanalysis fields, and satellite altimetry, following on the approach used in the tropical Pacific by Zilberman et al. (2013). Argo trajectories are used to provide a reference velocity, and the approach provides a well-constrained estimate of mean transport and time variability in the top 2000 m of the water column. During the Argo time period (from about 2004 to present) meridional transport is correlated with the Southern Annular Mode (SAM) (Figure 1c), but not with changes in El Niño and the Southern Oscillation (ENSO), as measured by the Niño 3.4 index (not shown). The total transport can be broken into parts and in Figure 1a the transport in the East Australia Current is correlated with the SAM, while its northward recirculation is anti-correlated with the SAM. The ocean interior, east of the dateline (dashed line in Figure 1b), is uncorrelated with the SAM (Zilberman et al. 2014).
- Narrow, western boundary currents strongly control poleward heat and mass transport, but they are not well sampled by Argo floats. In a close assessment of the East Australia Current, using observations from the high-resolution XBT line as well as Argo floats, the study shows that XBT sampling is superior, but that nonetheless, Argo provides a good measure of transport variability. This work is being extended to western boundary currents around the globe.
- South of the ACC in the Amundsen Sea Embayment, in situ ocean data are sparse, but available observations of Pine Island 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 the Amundsen Sea Embayment. Air-sea fluxes dominate the heat budget above the pycnocline, but do not appear to influence the denser water that is expected to contribute to basal melting. The model analysis supports the idea that heat is advected into the eastern end of the Embayment as a result of wind-stress-curl driven transport, and it is advected around the Embayment in a cyclonic gyre (Gilroy et al. 2013).
- Analyses of hydrographic data near West Antarctica indicate that Upper Circumpolar Deep Water (UCDW) is warming in parallel with the Southern Ocean as a whole. This suggests that UCDW warming originates in the Southern Ocean and is a response to oceanic processes rather than being a response to atmospheric warming.

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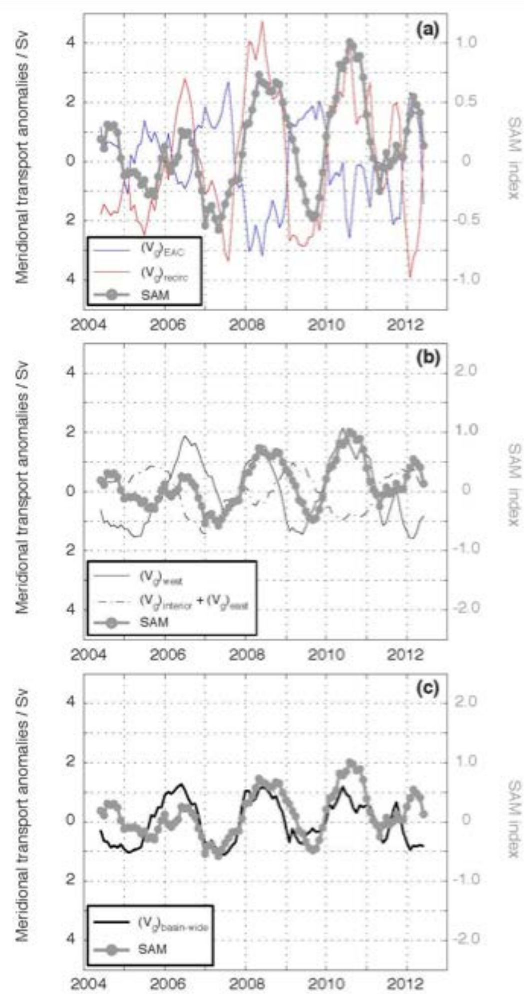

Figure 1. Time-series of 0-2000 m geostrophic transport anomaly (a) in the East Australia Current (EAC) (blue) and in the EAC recirculation region between 154.5° E and 180° (red), (b) in the western Pacific (continuous line) and east of the dateline (dashed line), and (c) basin-wide at 32° S, versus the SAM index for monthly values from 2004 to 2012.

Meridional Variability of the South Atlantic Meridional Overturning Circulation

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This project supports the development of a methodology to estimate heat transport variability using data mainly from satellite altimetry observations in combination with hydrographic data from XBTs and Argo profiling floats, and wind products from the National Center for Environmental Prediction (NCEP) reanalysis (Dong et al. 2011). This work is supported by NOAA/AOML and by NASA through its Ocean Surface Topography Science Team.

The Atlantic component of the Meridional Overturning Circulation (AMOC) is characterized by a northward flow of warm water in the upper layers from the South Atlantic into the North Atlantic, sinking and formation of North Atlantic Deep Water at high latitudes, and a southward return flow of cold water at depth. The AMOC carries a significant fraction of the total global ocean-atmosphere northward heat flux. The majority of this heat is lost to the atmosphere in the mid-latitudes where warm water meets cold, dry continental air masses. Several underway efforts involve in situ observations and numerical models seeking to design and establish a sustained observational system for the South Atlantic MOC.

This project incorporate satellite altimetry into these analyses to demonstrate how satellite measurements complement and expand the estimates of MOC from in situ observations in space and time in the South Atlantic. Of particular interest is to assess how well altimetry can be used to investigate the spatial and temporal variability of the MOC and Meridional Heat Transport (MHT) in this region. Special emphasis is given to the two areas of highest variability: the Brazil-Malvinas Confluence Region (Goni et al. 2011) and the Agulhas Retroflection region. Previous results from hydrographic observations showed that the geostrophic component dominates the MOC/MHT at 35°S (Dong et al. 2009). This project computes and analyzes the time series of the geostrophic and Ekman components of the MOC/MHT between 20°S and 35°S estimated from altimetry observations and NCEP winds. Preliminary results indicate that the MOC/MHT time series show that the geostrophic component dominates the interannual variability of MOC/MHT during 1993-2005, with Ekman component playing a large role after 2005. The mean values of MOC (MHT) (Figure 1) are 18.77 Sv (1.23 PW), 22.10 Sv (1.10 PW), 22.73 Sv (0.76 PW) and 23.06 Sv (0.72 PW) at 20°S, 25°S, 30°S, and 35°S respectively; denoting an increase in MHT towards the Equator, which is consistent with the very few estimates available in the region. The time series exhibit a long-period variability with high (low) values in the mid 2000's (1990's). The larger variability is observed at 20°S and 35°S, and it is lower in the center of the subtropical gyre. Consistent with previous results from XBT measurements, both geostrophic and Ekman components exhibit statistically significant annual cycle at 35°S with maximum anomalous values of approximately 4 Sv (0.5 PW). However, the seasonal cycles of the geostrophic and Ekman components are out of phase. Preliminary results also indicate that for the other three latitudes are similar to that at 35°S, but with weak annual cycle. Preliminary data obtained from this project are currently not available online.

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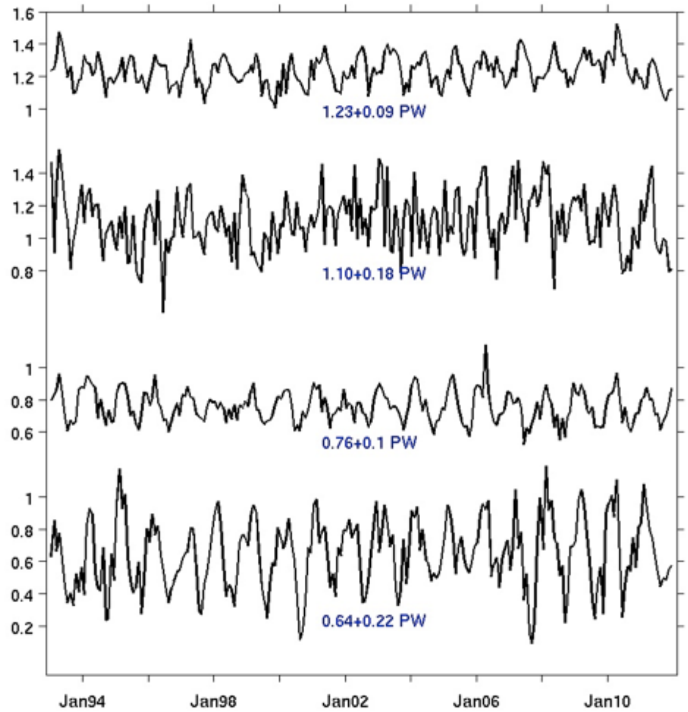

Figure 1. Meridional Heat transport in PW time series derived from satellite-altimetry observations for 20°S (top panel), 25°S, 30°S, and 34.5°S (bottom panel) since 1993.

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

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The long-term goal of the project is to understand, using all available satellite and in situ data in combination with a state-of-the-art ocean model, the nature of the North Atlantic Ocean circulation, with a particular emphasis on its decadal variability and climate consequences. The so-called Atlantic meridional overturning circulation (AMOC) is a simplified schematic of the complex North Atlantic Ocean circulation that is believed important to the climate system. While useful as shorthand for circulation changes (past, ongoing, and possibly in the future), a better understanding of its dynamics requires the description of the evolution of three-dimensional circulation patterns through time.

A main focus in 2013 was on the use of a new-generation fully global ocean state estimate by the ECCO project, termed ECCO-Production version 4 (v4) and covering the period 1992-2011 (Wunsch and Heimbach 2013a,b), to understand the dynamics of low-frequency SST and upper ocean heat content variability in the Atlantic. The analysis showcases the quantitative rigor that is feasible through the availability of state estimates with accurately closed property budgets, i.e., which fulfills known conservation laws exactly (Heimbach and Wunsch 2012). Detailed contributions of heat content variability from local air-sea heat fluxes, Ekman and geostrophic transports, and diffusive processes were inferred for the subpolar and subtropical gyres. Figure 1 shows the partition of heat content H variance of monthly anomalies in terms of its (a) total tendency, (b) advective convergence, (c) air-sea heat flux, and (d) diffusive convergence.

Recent results

- In the interior of subtropical gyre, local forcing explains the majority of H variance on all timescales resolved by the ECCO estimate.
- In the Gulf Stream region, low-frequency H anomalies are forced by geostrophic convergences and damped by air-sea heat fluxes.
- In the interior of the subpolar gyre, diffusion and bolus transports play a leading order role in H variability, and these transports are correlated to low-frequency variability in wintertime mixed layer depths.

Key transport and other climate indices inferred from v4 were provided to NOAA's annual State of the Climate report (Baringer et al. 2013), and are showcased in several chapters of the new, 2nd edition of the WOCE book (Baringer and MacDonald 2013; Speer and Forget 2013; Wunsch and Heimbach 2013b).

A third thrust was the discussion of the role of circulation changes in the North Atlantic in the observed speed-up, thinning, retreat, and corresponding mass loss of Greenland's marine-terminating outlet glaciers over the last decade (Straneo and Heimbach 2013; Straneo et al. 2013).

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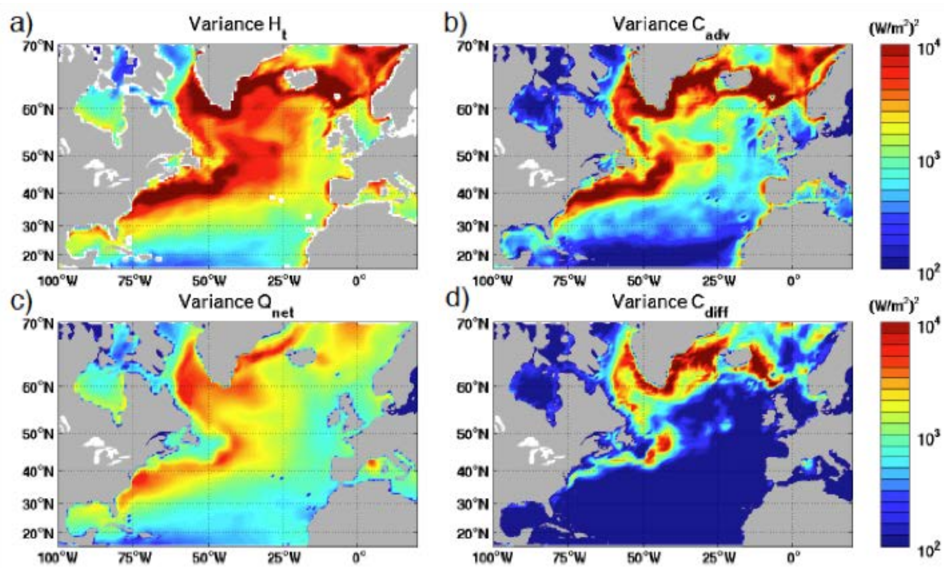

Figure 1. The partition of heat content H variance of monthly anomalies in terms of its (a) total tendency, (b) advective convergence, (c) air-sea heat flux, and (d) diffusive convergence.

Collaborative Research: An Eddy-Permitting Arctic & Sub-Polar State Estimate for Climate Research (ASTE)

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The goal of the project is the production of an eddy-permitting Arctic and sub-polar North Atlantic state estimate (ASTE) for climate research, using basic tools developed within the Estimating the Circulation and Climate of the Ocean (ECCO) consortium. The coupled ocean—sea ice general circulation model (MITgcm) is being constrained by as many ocean and sea ice observations as available and practical. The target period is from 1992 to present. The fit is achieved through minimization of a least-squares misfit function (adjoint or Lagrange Multiplier method). The coupled ocean—sea ice adjoint model has been generated by means of algorithmic differentiation. The ASTE domain covers the Atlantic northward of 35.4°S and the entire Arctic, with the exception of the Pacific sector southward of Bering Strait (50.7°N). The horizontal resolution is initially 12 to 30 km with 50 vertical levels. Open boundaries are obtained from a new-generation global ECCO-Production solution (“version 4”) (Wunsch and Heimbach 2013a,b). The control space comprises the initial conditions of the coupled ocean—sea ice state, the time-varying surface atmospheric state, time-varying open boundary conditions, and spatially varying model parameters.

A number of Arctic/North Atlantic-specific datasets have been prepared for use in ASTE (in general, this refers to devising appropriate online model-data misfit operators, the provision of uncertainty estimates that include adequate representation errors, and the provision of the datasets in the right format). For each of these datasets the model computes online model-data misfits' terms, which in turn act as "forcing terms" of the adjoint model integration. They comprise: the complete ECCO-Production data repository (especially satellite data and Argo); ice thickness estimates from ICESat; ice velocity estimates from satellite; ice-Tethered Profiler (ITP) data; Arctic river runoff from R-ArcticNET; SCICEX data; in situ data from ASOF and AWI for Nordic Seas; improved and reprocessed sea ice concentration and uncertainty products; and improved treatment of hydrographic climatologies. By way of example, Figure 1 shows the reduction in misfit between simulated hydrography and measurements along several sections across the Atlantic. Preliminary cost reductions of 22% have been obtained after two iterations.

Recent results

- Determination of mass and enthalpy budgets and associated ocean-ice-atmosphere fluxes during sea ice quasi-equilibrium state in the Labrador Sea and Baffin Bay, and analysis what sets the sea ice quasi-equilibrium extent (Fenty and Heimbach 2013a,b).
- Inference of sources, pathways, and seasonal development of upper halocline waters in the Western Arctic Ocean, with implications for heat advection through the Chukchi Sea and Canada Basin (Nguyen et al. 2012).
- A preliminary analysis of the role of perennial sea ice in the observed Arctic sea ice decline (Rampal, Heimbach, and Kwok, in prep.).
- Initial analysis of decadal North Atlantic SST and AMOC variability (Buckley et al. 2014; Wunsch and Heimbach 2013a,b).
- An assessment of atmospheric reanalysis products over the Arctic, with implications for uncertainty estimates (Chaudhury et al. 2013a,b).

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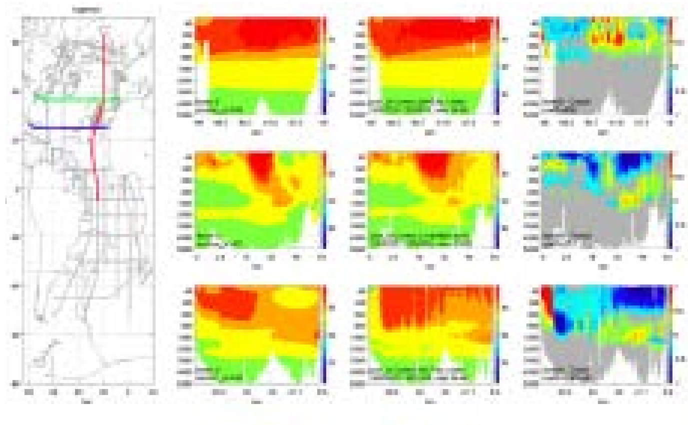
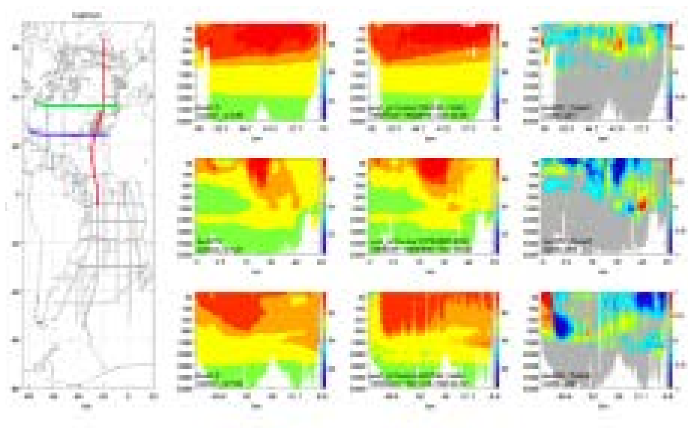


(a) Iteration 0



(b) Iteration 3

Figure 1. Cost reduction in salinity across lines A05 (top panel, blue line in world map), AR21 (middle panel, red in map), and A03 (bottom, green) in the Central Atlantic Ocean. Iter03 shows improvement in the upper 1000 m of the whole North Atlantic. Along line A03 at 36°N, an improvement in the separation of the Gulf Stream can be seen. The net cost reduction in these three sections ranges from 32% to 56%.

Influence of the Continental Ice Retreat on Future Global Climate

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

Recent results

Evidence from observations indicates a net loss of global land-based ice and a rise of global sea level. Other than sea level rise, it is not clear how this loss of land-based ice could affect other aspects of global climate in the future. Here, the project uses the Community Climate System Model version 3 to evaluate the potential influence of shrinking land-based ice on the Atlantic meridional overturning circulation (AMOC) and surface climate in the next two centuries under the IPCC A1B scenario with prescribed rates of melting for the

Greenland Ice Sheet, Western Antarctic Ice Sheet, and mountain glaciers and ice caps. Results show that the AMOC, in general, is only sensitive to the freshwater discharge directly into the North Atlantic (NA) in the next two centuries. If the loss of the Western Antarctic Ice Sheet wouldn't significantly increase from its current rate, it would not have much effect on the AMOC. The AMOC slows down further only when the surface freshwater input, due to runoff from land-based ice melt, becomes large enough to generate a net freshwater gain in the upper NA. This further weakened AMOC does not cool the global mean climate, but it does cause less warming, especially in the Northern high latitudes in general and in Europe in particular. The projected precipitation increase in North America in the standard run becomes a net reduction in the simulation that includes land ice runoff. However, there are precipitation increases in west Australia in the simulations where the AMOC slows down due to the inclusion of land-based ice runoff.

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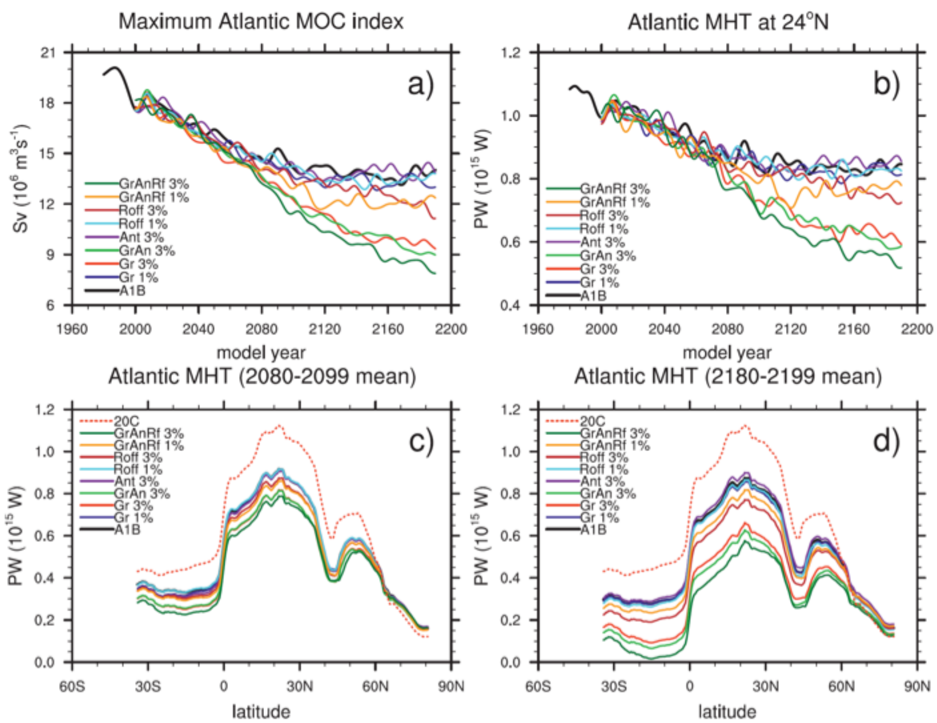

Figure 1. Changes of the MOC and MHT in the Atlantic: a) time-evolving AMOC index; b) time-evolving Atlantic MHT at 24oN; c) the annual mean Atlantic MHT averaged over 2080-2099 for the sensitivity simulations and averaged over 1980-1999 (20°C); d) the annual mean Atlantic MHT averaged over 2180-2199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

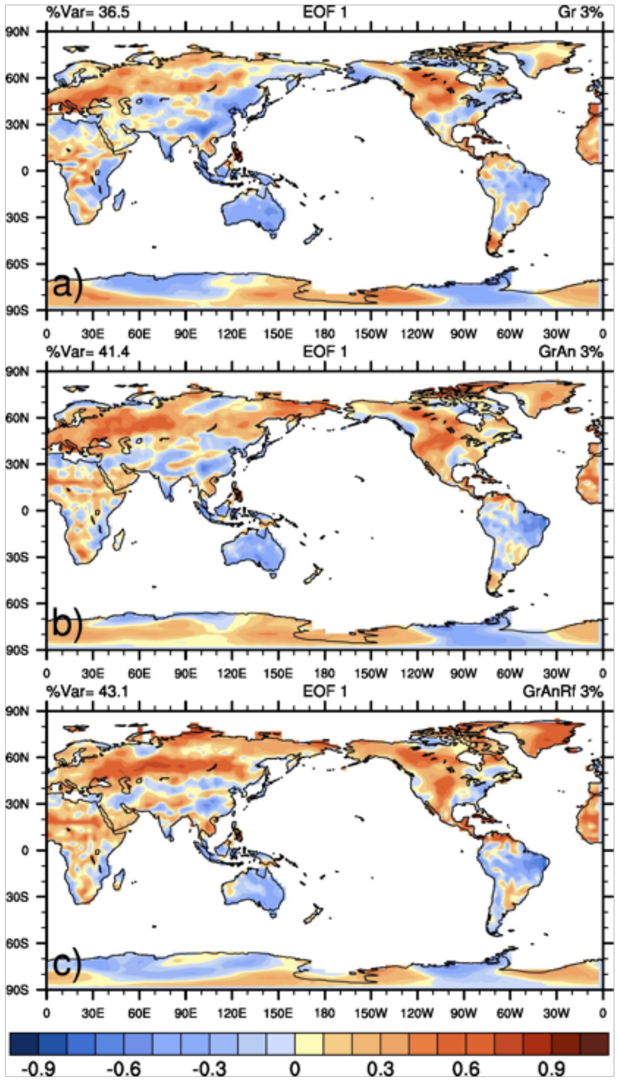

Figure 2. Correlation of the land precipitation anomalies relative to the A1Bexp with the first EOF of the Pacific SST anomalies relative to A1Bexp: a) Gr 3% simulation; b) GrAn 3% simulation; c) GrAnRf 3% simulation. Contour interval is 0.1. Notes: Gr 1% and Gr 3% are simulations with an initial Greenland Ice Sheet melt of 0.01 Sv and increases 1% or 3% per year until 2100. Roff 1% and Roff 3% are simulations with an initial glacier and mountain ice caps melt of 0.01 Sv and increases 1% or 3% per year until 2100. The Ant 3% is the simulation with an initial Western Antarctic Ice Sheet melt of 0.002 Sv and increases 3% per year until 2100. The GrAn 3% is the simulation including both Greenland (0.01 Sv) and Western Antarctic (0.002 Sv) ice sheet melt and increases 3% per year until 2100. The GrAnRf 1% and GrAnRf 3% are simulations including all land-based ice loss and increases 1% or 3% per year until 2100. The A1Bexp is a simulation under A1B scenario without consideration of land-based ice loss.

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

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

Recent results

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

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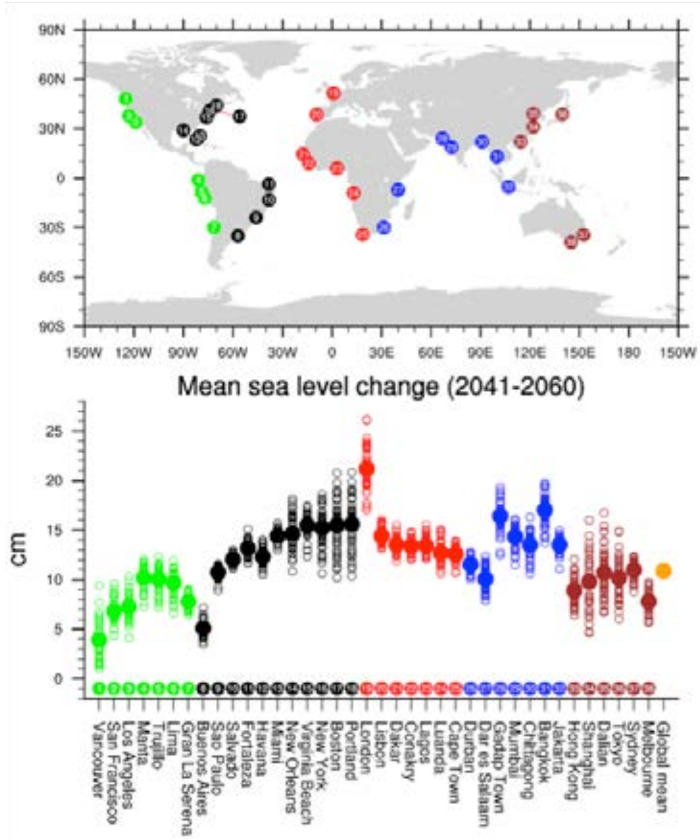

Figure 1. Simulated change in sea level (cm) between the periods 2041–2060 and 1980–1999 at selected coastal cities from the 40-member CCSM3 ensemble. The top panel shows the city locations, color-coded by region. The bottom panel shows the sea level changes using the same regional color-coding, with open circles for each of the 40 ensemble members and filled circles for the ensemble mean.

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

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International Collaborators: D. Smeed[3], G. McCarthy[3], E. Frajka-Williams[3], and S. Cunningham[4]
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The objective of this program is to continuously monitor the strength and structure of the Atlantic meridional overturning circulation and meridional ocean heat transport at 26.5°N using a basin-wide observing system. As of October 2012 the project had 8.5 years of data in hand from the full trans-basin array. Funding for the array has recently been continued through 2020.

Recent results

The mean values for the AMOC strength and northward heat transport from the time series collected thus far, from 2004-2012, are 17.5 Sv and 1.25 PW, respectively. The mean heat transport value of 1.25 PW is lower by almost 0.1 PW than the value of 1.33 PW reported by Johns et al. (2011) based on the first four years of data. 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 <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. Significant cooling in the mid-latitude North Atlantic from 2009-2011 has been linked to the reduced heat transport across 26.5°N.

Significant findings include:

- A statistically significant downtrend has occurred in the AMOC from 2004-2012, which is believed to be part of a secular (rather than anthropogenic) change (Smeed et al. 2013).
- 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 (Cunningham et al. 2013). The heat transport divergence between 26.5°N and 41°N can approximately explain the magnitude and timing of this event.
- Essentially all of the interannual variability that has occurred in the meridional heat transport is contained in the overturning component of the heat transport, while the gyre component has maintained a stable mean value.
- Most of the observed interannual variability in the AMOC that is not related to Ekman transport appears to be linked to wind-forced mid-ocean variability associated with first baroclinic mode Rossby waves, that are excited by interannual wind stress curl anomalies in the central and western part of the basin.

Online data

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

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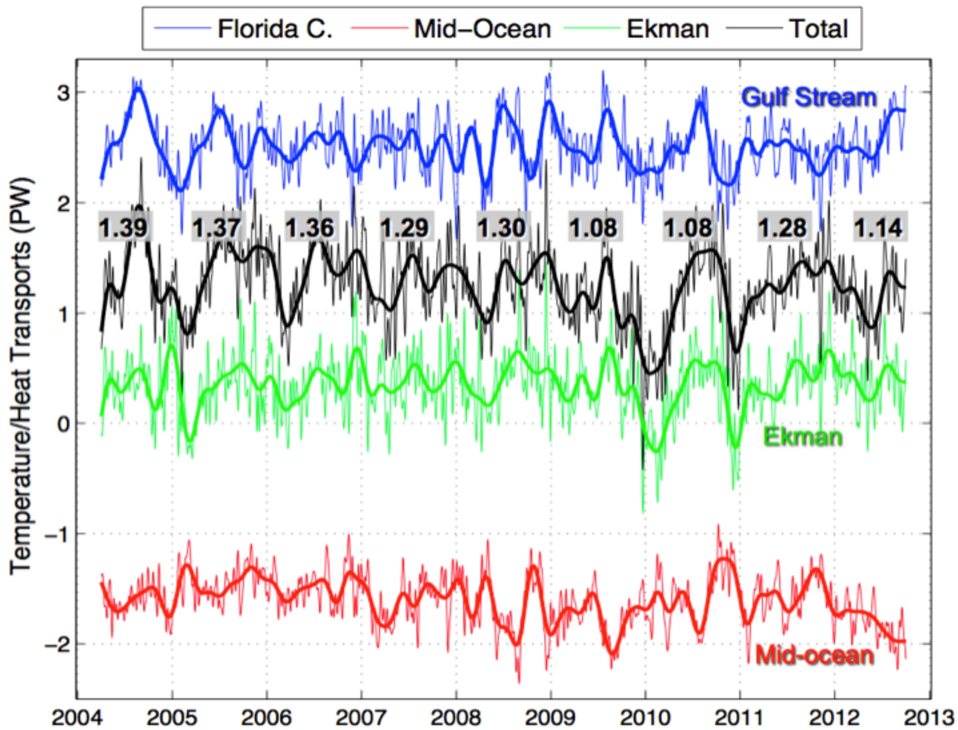

Figure 1. Time series of the meridional heat transport (black), and the contributions by the temperature transport of the Florida Current (blue), the Ekman layer (green), and the mid-ocean region from the Bahamas to Africa (red). High-frequency data are 10-day averages and smooth curves represent 90-day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

The Contributions of Ocean Circulation to North Atlantic SST

PIs: K. Kelly[1] and S. Dickinson[1]
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The goal of this project is to determine the relative importance of air-sea fluxes and ocean circulation to interannual sea surface temperature anomalies in the North Atlantic Ocean, in particular, whether advection contributes to such large-scale SST patterns as the Atlantic Multidecadal Oscillation (AMO).

Recent results

- Assuming that SST represents the mixed-layer temperature a budget was estimated for temperature tendency, consisting of surface heat fluxes, horizontal advection and diffusion, and contributions from changes in the vertical structure of temperature. Many of these terms are difficult to estimate and estimates based on observations showed little correlation with temperature tendency, suggesting high levels of error or neglect of important terms.
- However, heat content anomalies (Figure 1) show low frequency patterns and time series that are quite similar to those of SST (the AMO is defined as the first empirical orthogonal function (EOF) of

SST). This suggests a simpler and less error-prone analysis: the contributions to heat content anomalies, which are surface fluxes and horizontal heat transport. For a sufficiently accurate flux product, the transport can be estimated as the residual of the heat content budget.

- Using altimetric sea surface height (SSH) anomalies as a proxy for heat content, the project examined heat content budgets for the three regions of the dominant tripole pattern of the AMO and found that in each region heat transport anomalies made a larger contribution than the anomalies of surface fluxes.
- This analysis suggests that the dominant contribution to the AMO is anomalous ocean circulation, rather than air-sea heat fluxes. This analysis will be repeated with another flux product.

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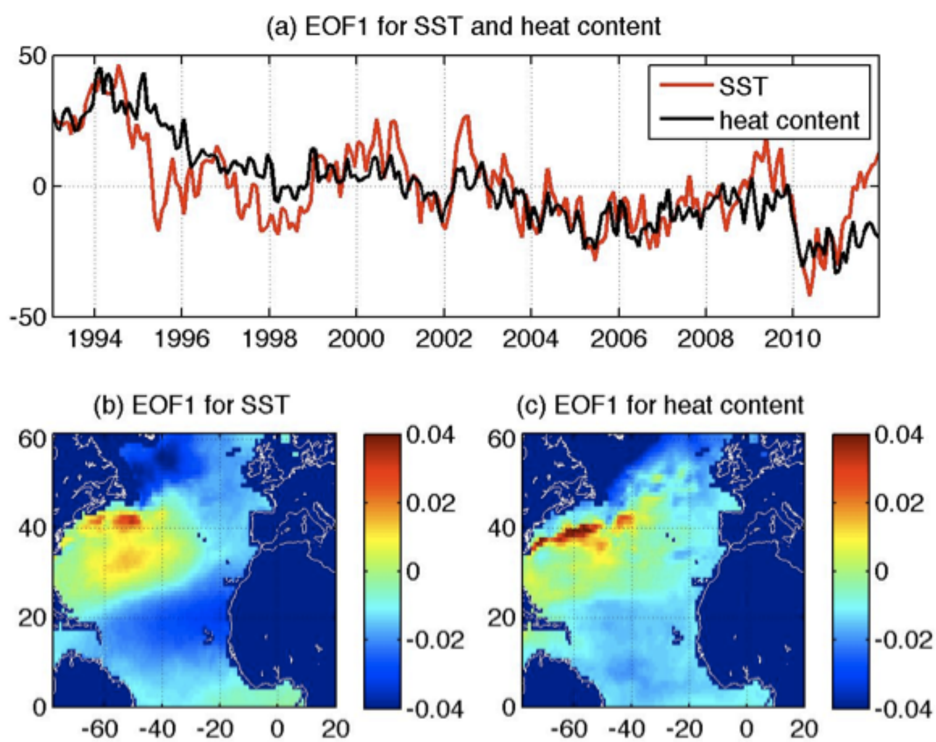

Figure 1. First EOFs of SST (the Atlantic Multidecadal Oscillation) and heat content (derived from SSH). (a) Time series, (b) SST and (c) heat content. Units are degrees C and Joules, respectively. Heat content time series is scaled for plot.

Assessing Meridional Transports in the North Atlantic Ocean

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The goal of this study is to explain the causes of interannual to decadal anomalies of meridional heat and freshwater transport in the Atlantic Basin using analysis of both observations and model output. Satellite observations of sea level, sea surface height, mass, and in situ based estimates of heat storage, observationally constrained surface fluxes as well as output from both ocean only and coupled climate models are all used in the analyses. In addition, the project is examining the impact of changes in transport and storage of heat in the ocean on the atmosphere.

Recent results

- An analysis of the contributions to North Atlantic sea level variability by graduate student J. Zhang along with Thompson and Kelly showed that surface heating makes a substantial nonseasonal contribution in the subpolar gyre annual sea level changes and that the Sverdrup Balance with weak modification by topography explains much of the intergyre variability on annual time scales.
- Zhang, Thompson, and Kelly analysis of the meridional structure of the meridional heat transport in the Atlantic find that the principal pattern of variability on interannual times scales is symmetric about the equator. This result is consistent across multiple model simulations, both a hindcast of the last 50 years as well as five different historical couple climate model simulations from the Climate Modeling Intercomparison Project Version 5 (CMIP5) archive. The pattern has significant skill up to 20°N, suggesting that the variability even at the latitude of RAPID/MOCHA may be of tropical origin.
- Kelly and Thompson, in collaboration with J. Lyman at PMEL, completed an analysis of the Atlantic heat and mass budgets assimilating thermosteric sea level, equivalent water thickness (from GRACE) and sea level anomalies. The analysis revealed a high degree of meridional heat transport (MHT) coherence, from 30°S to 40°N. It also showed that increased (decreased) MHT corresponds to increased (decreased) heat loss. Good agreement was found with the MHT estimates from the RAPID/MOCHA programs (Figure 1). The manuscript has been accepted for publication in Journal of Climate.
- A lagged correlation analysis between interannual sea surface height (SSH, as a proxy for upper ocean heat content) and surface turbulent heat flux (OAFLUX, Objectively Analyzed Air-sea Flux) shows that throughout much of the North Atlantic, SSH is lagged correlated with surface turbulent heat flux, by several months throughout much of the North Atlantic Basin. A comparison of the same analysis using SST shows that SSH has more predictive skill for surface turbulent heat flux than does SST. A feedback analysis is used to identify the regions and the times of the year when stored heat in the ocean can force surface turbulent heat flux anomalies. Findings show that the eighteen degree water regions exert the strongest control on air-sea turbulent heat fluxes, indicating that the stored heat anomalies in the mode water can force changes in the atmosphere. A manuscript is in preparation for Journal of Climate.

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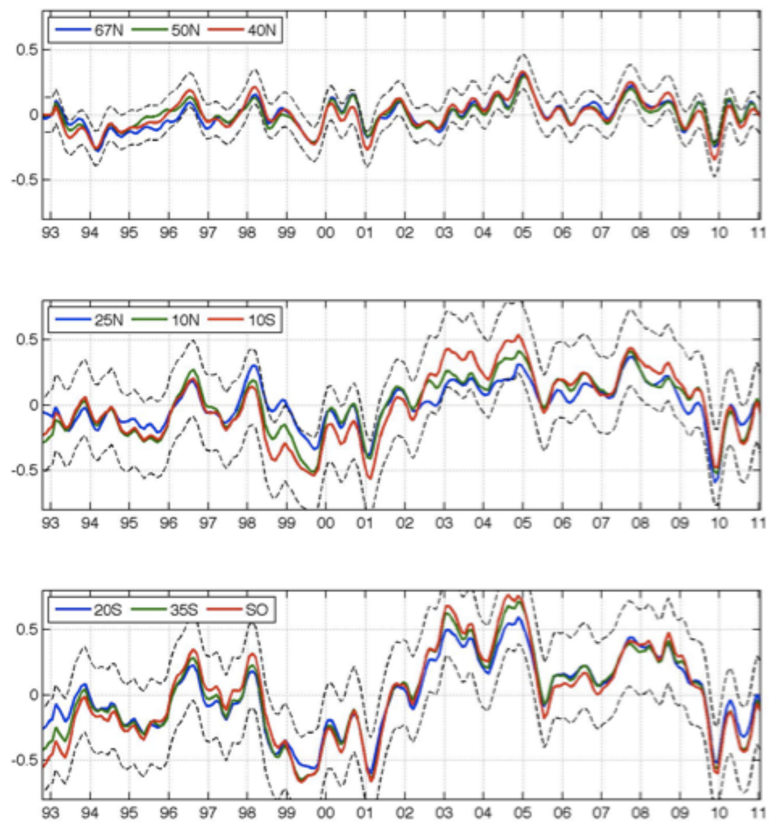

Figure 1. Meridional Heat Transport (MHT) anomalies inferred from SSH using a simple model of the Atlantic Ocean heat budget. MHT was set to observed values at 41°N from Willis (2010). Error bars are shown for 40°N, 10°N, and 35°S (thin dashed lines). Units are Petawatts.

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

PIs: C. M. Lee[1], J. I. Gobat[1], K. Stafford[1] and R. Moritz[1]

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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.

Recent results

- The observations show large interannual variability in volume and freshwater transport, with no clear trends observed between 2004-2010 (Curry et al. 2013). Average volume, liquid freshwater and sea ice transports are -1.6 ± 0.2 Sv, -93 ± 6 mSv and -10 ± 1 mSv, respectively (negative indicates southward transport). However, changes in circulation have occurred, as freshwater outflow from Baffin Bay has decreased and warm, salty North Atlantic inflow has increased since 1987-1990. Local atmospheric variability within Baffin Bay and the Labrador Sea influence the observed variability in Davis Strait volume transport either directly or indirectly. Large-scale atmospheric teleconnections, such as the AO and NAO, correlate poorly with Davis Strait volume transport and are likely only an indicator of transport variability when the indices are strong. Efforts have also focused on attributing variability in narrowly defined quantities, such as the mean salinity of the Arctic outflow. 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 freshwater signature also observed over the North Ellesmere Shelf (Jackson et al. 2014) earlier in the year (January 2009).
- Azetsu-Scott et al. (2012) use oxygen isotope composition to document the relative freshwater and freshwater 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.
- The first year-round occupation of an Arctic region by autonomous gliders was 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. This includes five months of operations beneath sea ice and two months in marginal ice conditions. These missions provide a year-round time series of high-resolution sections across the Strait.

Online data

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OSNAP: Overturning in the Subpolar North Atlantic Program

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A US-led international program, Overturning in the Subpolar North Atlantic (OSNAP), designed to provide a continuous record of the full water column, transbasin fluxes of heat, mass and freshwater in the subpolar North Atlantic, was funded by NSF in September of 2013 and is planned for deployment in the summer of 2014 for a duration of four years. OSNAP has substantial international collaboration, including measurement contributions from the US, UK, Germany, the Netherlands and Canada. The OSNAP observing system (Figures 1 and 2) consists of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West), and the second from the southeastern tip of Greenland to Scotland (OSNAP East). The observing system also includes subsurface floats (OSNAP Floats) in order to trace the pathways of overflow waters in the basin and to assess the connectivity of currents crossing the OSNAP line.

The location of the OSNAP East and West legs purposefully melds with a number of long-term observational efforts in the North Atlantic: the Canadian repeat AR7W program in the Labrador Sea; the German Labrador Sea western boundary array at 53°N; the global Ocean Observatories Initiative node to be placed in the southwestern Irminger Sea; the repeat A1E/AR7E hydrographic sections across the Irminger and Iceland basins; and the Ellett line in the Rockall region. OSNAP, in conjunction with the RAPID/MOCHA array at 26°N and the EU THOR/NACLIM program, will provide a comprehensive measure of the Atlantic Meridional Overturning Circulation (AMOC) and provide a means to evaluate intergyre connectivity in the North Atlantic. Details on the observing system design are given in Figure 2.

The specific OSNAP objectives are:

1. Quantify the subpolar AMOC and its intra-seasonal to interannual variability via overturning metrics, including associated fluxes of heat and freshwater.
2. Determine the pathways of overflow waters in the NASPG to investigate the connectivity of the deep boundary current system.
3. Relate AMOC variability to deepwater mass variability and basin-scale wind forcing.
4. Determine the nature and degree of the subpolar-subtropical AMOC connectivity.
5. Determine from new OSNAP measurements the configuration of an optimally efficient long-term AMOC monitoring system in the NASPG.

The first two objectives will be met via the OSNAP observing system, while the latter three goals will be achieved in coordination with ongoing and planned programs.

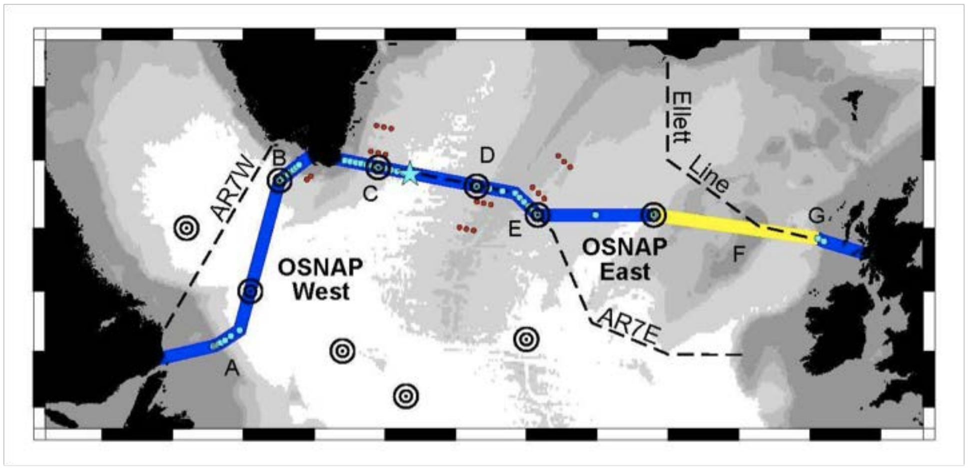

Figure 1. OSNAP elements: (A) German 53°N western boundary array and Canadian shelfbreak array; (B) US West Greenland boundary array; (C) US/UK East Greenland boundary array; (D) Netherlands western Mid-Atlantic Ridge array; (E) US eastern Mid-Atlantic Ridge array; (F) UK glider survey over the Hatton-Rockall Bank and Rockall Trough; (G) UK Scottish Slope current array. Red dots: US float launch sites. Blue star: US OOI Irminger Sea global node. Black concentric circles: US sound sources.

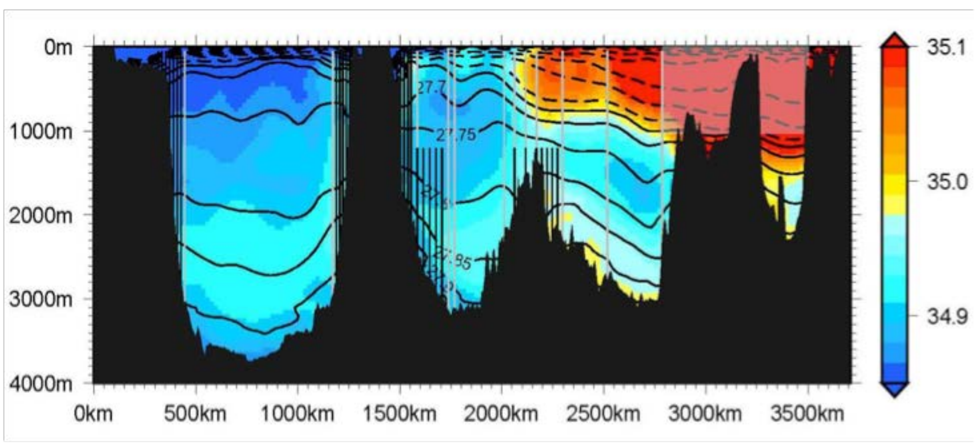

Figure 2. Proposed OSNAP array superposed on climatological salinity along the OSNAP West (leftmost basin) and East lines. Color shading is mean salinity (psu); black solid (dashed) lines are isopycnals at 0.05 (0.10) kg m-3 intervals. Proposed mooring locations (vertical lines) and glider domain (shaded box) are indicated. To reconstruct the velocity field, we plan to directly measure the currents at the boundaries and the flanks of the Reykjanes Ridge and then use T/S sensors and gliders to estimate the interior geostrophic velocities. Black moorings indicate where the velocity field is directly sampled. Gray moorings double as direct velocity measures and endpoints for the geostrophic regions.

Dynamics of the Descending Branch of the Atlantic Meridional Overturning Circulation

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The overall goal of the 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).

In Schloesser et al. (2012), the study explores the dynamics of the descending branch of meridional overturning circulations (MOCs), by obtaining analytic solutions to a variable-density, 2-layer model (VLOM) forced only by a surface buoyancy flux. 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 p*(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). Key processes involved are 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.

Schloesser et al. (2013) was an extension of the Schloesser et al. (2012) study to include forcing by a zonal wind stress. Much of the paper is devoted to the derivation and analysis of analytic solutions to VLOM. For validation, the study also reports corresponding numerical solutions to an ocean general circulation model (OGCM). The wind stress drives subtropical and subpolar gyres, and in a standard solution the latter extends north of y_2. Vertical diffusion is not included in VLOM (minimized in the OGCM). Consequently, the MOC is not closed by upwelling associated with interior diffusion, but rather by flow through the southern boundary of the basin (into a southern-boundary sponge layer in the OGCM), and solutions are uniquely determined by specifying the strength of that flow or the thermocline depth along the tropical eastern boundary.

Solutions also forced by winds differ markedly from those forced only by p*(y) 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 wind-driven 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 deepwater south of the Subpolar Gyre, M, the latter being a better measure of large-scale MOC strength. When western-boundary upwelling occurs in the solutions, M is independent of the diapycnal processes in the subpolar ocean.

In Furue et al. (2013), the project has started to explore the impact of continental shelf, by including an eastern-boundary continental shelf in our 2-layer model. The interface beneath layer one intersects the continental slope along a "grounding" line, such that the basin is divided into offshore and coastal regimes where the model consists of two layers and one layer, respectively. The solution demonstrates that the continental slope strongly inhibits the offshore propagation of Rossby waves: onshore of the grounding line (where the model is a 1-layer system), Rossby-wave characteristics, which would otherwise be oriented due westward, are oriented much more along the shelf due to the topographic-β effect. As a result, a barotropic, poleward coastal current is confined to the slope in layer one, providing an additional pathway for the MOC surface branch.

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

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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

To characterize decadal and multidecadal variability of the AMOC transport, the project used historical hydrographic data to derive a multidecadal transport timeseries of the North Brazil Current (NBC), a major conduit across the equator in the upper branch of AMOC. It demonstrated that the NBC transport is a robust indicator of the decadal-multidecadal variability of AMOC using model results and observational evidence (Zhang et al. 2011).

The project then investigated the relationship between the inferred AMOC transport variability and the temperature (T) and salinity (S) variations in historical records in the North Atlantic thermocline, along path of the upper branch of AMOC. The identified relationships from observational analyses are consistent with the diagnostics of model outputs from the NCAR ocean-sea ice model forced by interannual CORE II forcing. Results suggest that:

1. Decadal variability of T/S in the thermocline east of Abaco is positively correlated to the AMOC transport variability, but anti-correlated to the T/S variability in the tropical North Atlantic.
2. The anticorrelation between T/S in the western subtropical and tropical North Atlantic themocline is regulated by the variation of subtropical cell (STC): stronger or weaker STC transports more or less saline subtropical water into the tropics leaving freshening or saline anomalies in the subtropics. The STC is on the other hand anti-correlated with the AMOC transport.
3. Further, the upper ocean T/S anomalies east of Abaco lead the variability in the eastern subpolar gyre, suggesting at least part of the observed salinity anomalies in the eastern subpolar gyre can be originated from the subtropics.

To elucidate the possible connection of the observed tracer CFC11/12 variability in the Deep Western Boundary Current (DWBC) east of Abaco (Molinari et al. 1998) and the AMOC, the project developed a Sigma-1 coordinate HYCOM that is found to be superior than the traditional Sigma-2 coordinate model in simulating the AMOC (Bleck et al. 2013). The model was then integrated for ~300 years forced by five cycles of 60-year CORE II forcing. CFC11 tracer was added in the simulation during the last 60-year integration to investigate the decadal variations of CFC11 in Labrador Sea Water (LSW) along the DWBC from Labrador Sea to Abaco and related them to variations of AMOC and Labrador Sea ventilation. Major results include:

1. Large decadal variability of AMOC transport is simulated and attributed to modeled decadal variations of ventilation of the LSW, which compares well with observation.
2. Decadal time scale variability of CFC11 in the DWBC in the subtropical gyre is identified by the deviations from the overall shape of increasing CFC11 atmospheric history, and is correlated with the AMOC transport variability.
3. This CFC11 decadal variation is only found south of the Gulf Stream, suggesting it is originated from dynamical processes related to the AMOC variation at the crossover of the Gulf Stream and DWBC, rather than the tracer source in the Labrador Sea.

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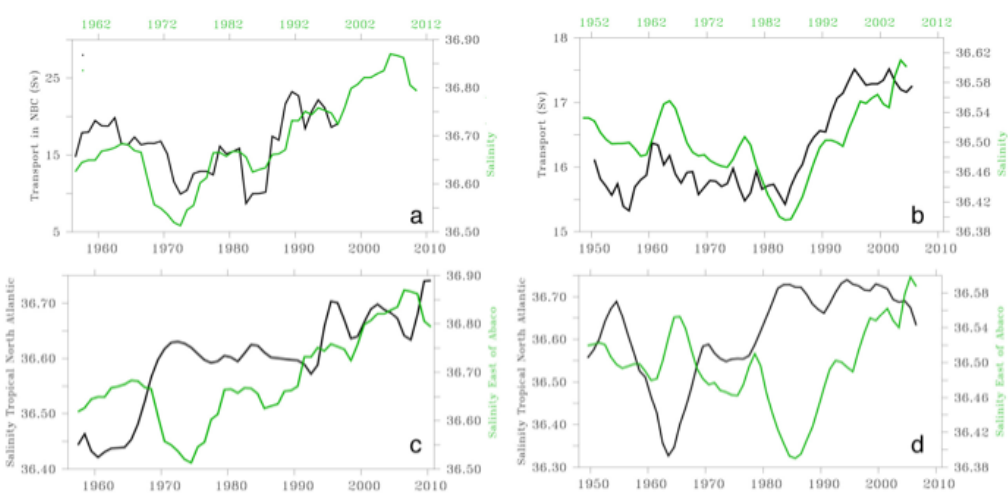

Figure 1. AMOC transport at 6°S and salinity (green) in the thermocline east of Abaco (a: observation, AMOC transport is inferred from NBC; b: NCAR ocean—sea ice mode); Salinty in the tropical North Atlantic thermocline (averaged over 55°W - 30°W, 10°N - 15°N, south of salinity maximum region) and east of Abaco (c: observation; d: NCAR ocean—sea ice model).

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. The SAM array has now collected more than four years of data, and the array has been completely recovered and redeployed (in December 2012) with batteries that will last through 2016. Very excitingly, the Brazilian partners essentially doubled the number of moored instruments with new deployments in December 2012, and the French partners deployed a comparable array on the eastern boundary in September 2013. Finally, the South African partners will be further augmenting the eastern array in early 2014 – so a true trans-basin array at 34.5°S is taking shape.

The first publication based primarily on the SAM data was published in November 2012 in the journal Ocean Science. The results of that study show that the Deep Western Boundary Current (DWBC) is highly variable at 34.5°S, with volume transport variations of 40+ Sv occurring on time scales of a few days and anomalies of 20+ Sv persisting for several months. This study also showed that 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. Comparison to 27-years of output from a high-resolution global model, the ocean general circulation model for the Earth simulator (OFES), indicated that at least approximately five 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.

Another publication based on the SAM data, as well as data from a pilot French array on the eastern boundary, is currently in press in the Journal of Geophysical Research. The 20-months of data used in this study demonstrate that the variability of the basin-wide MOC at 34.5°S is of comparable magnitude to that observed in the longer 26.5°N record. The variations in the South Atlantic MOC at 34.5°S are driven roughly evenly by changes on the western and eastern boundaries for time scales that can be observed in a 20-month record (i.e. days to a few months). Longer records will be required to see whether this equal distribution persists at annual and/or longer time scales.

More information and the raw data from the NOAA instruments is available online: www.aoml.noaa.gov/phod/research/moc/samoc/sam/

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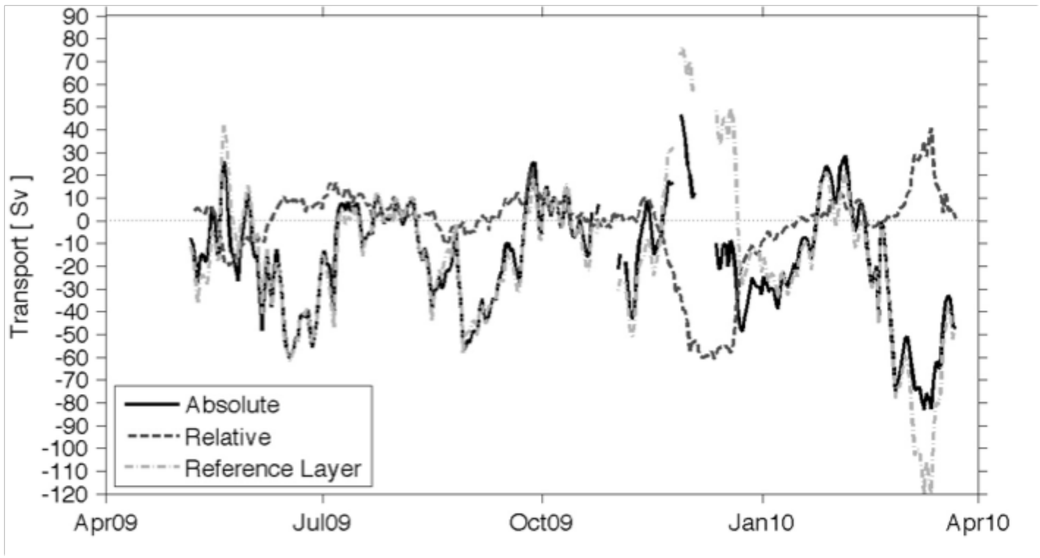

Figure 1. Transport of the Deep Western Boundary Current at 34.5°S, integrated between 51.5°W and 44.5°W and between 800 and 4800 dbar (or the bottom, where it is shallower). The total absolute transport is shown (solid black line), as is the transport determined relative to an assumed level of no motion 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.

Collaborative Research: Variability, stochastic dynamics, and Compensating Model Errors of the Atlantic Meridional Ocean Circulation in Coupled IPCC models

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General circulation models (GCMs) play a crucial role in identifying the behavior of the Atlantic Meridional Overturning Circulation (AMOC) and its relationship to abrupt climate change. The project is using dynamically based statistical methods at multiple timescales, both in the frequency and in the temporal domains to explore the interplay of deterministic and stochastic processes and their role in the predictability of the AMOC and Atlantic Climate, including the identification of systematic compensating model errors in AMOC simulations in IPCC GCMs. Applying Linear Inverse Modeling (LIM; Penland and Sardeshmukh 1995) to the output of each GCM summarizes nonlocal interactions between temperature and salinity resolved at the annual timescale, while estimating frequency-dependent transfer functions (transfer function analysis, or TFA; MacMynowski and Tziperman 2010) between these variables. Using these methods in combination aids the research in separating forced-response multivariate phenomena from processes whose transient behaviors are coupled but operate on different timescales.

Phase information from TFA and Fluctuation-Dissipation theory will be combined with LIM results to estimate the subscale forcing, both atmospheric and oceanic, required to maintain the AMOC as represented in each model. The proposed study will localize the sensitive regions affecting the AMOC in each model, identify sources of that sensitivity, diagnose compensating model errors, and allow comparison of results among the different models.

This collaborative research project began in September of 2013. During the months remaining in that calendar year, the PIs decided to leverage work done by Penland and Hartten (2014), adding an analysis that will allow identification of a target time series representing subscale stochastic forcing of stream function. The project also identified models to be considered, collected output from these models, and planned meetings to discuss progress and preliminary results.

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South Atlantic Meridional Overturning Circulation: Pathways and Modes of Variability

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

Recent results

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

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

Lastly, using observations and simulations by the NOAA/GFDL CM2.5 high-resolution, eddy-permitting, coupled climate model and an ocean-only (CORE forced) version of the same model, the project analyzed the sensitivity of the seasonal cycle of the maximum northward volume transport by the MOC to wind forcing at the latitudes of the RAPID/MOCHA array (nominally 26.5°N) and the developing SAMBA array (nominally 34.5°S). Observation-based estimates of the annual cycle of volume transport by the MOC suggest that both geostrophic and directly wind-driven Ekman components contribute to the annual cycle in observations, and are in (out of) phase at 26.5°N (34.5°S), leading to very different total MOC seasonal cycles. Although the model simulations are able to reproduce the observed total MOC seasonal variations at 26.5°N, none of the model simulations are able to reproduce the observed geostrophic seasonal variations at 34.5°S leading to an overly strong total MOC seasonal cycle. Using a two-layer idealized ocean model (Zhao and Johns, 2014), the project is investigating whether the weak geostrophic seasonal cycle in the coupled model and ocean-only simulations in the South Atlantic is due to excessively strong baroclinicity below the surface mixed layer in the models as suggested by Dong et al. (2014).

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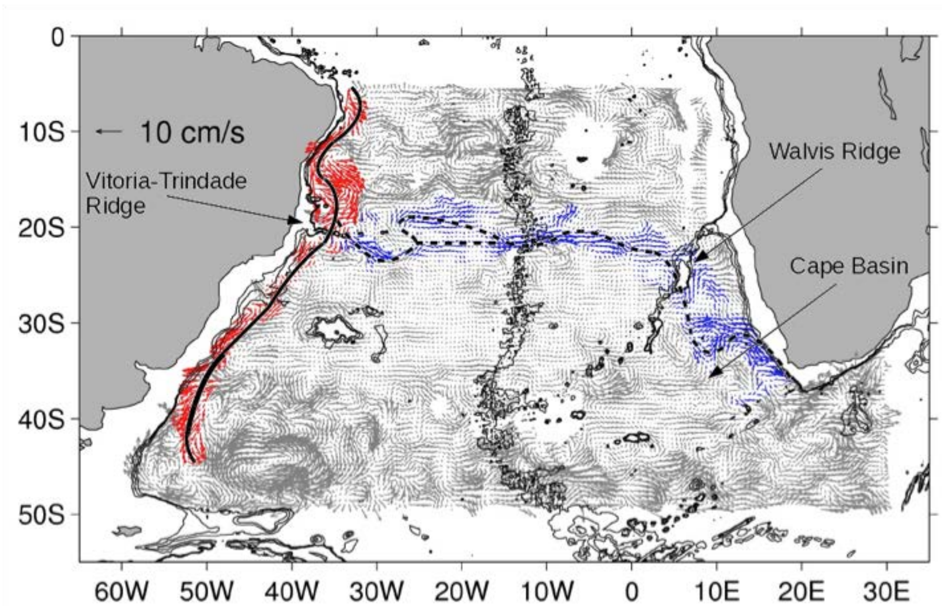

Figure 1. Velocity field at 2000 dbar derived from Argo data. Red highlights the strong southward flow along the western boundary; blue indicates the eastward velocity originating near the Vitória-Trindade ridge. Black lines: 2000, 2500 and 3000 m isobaths. Solid curves highlight the pathways of the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

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

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

Recent results

The project has completed a synthesis of the 12 moorings across Denmark Strait north of the sill (known as the KOGUR array), THOR moorings, an extensive hydrographic/velocity/tracer survey of the East Greenland Current from Denmark Strait to Fram Strait, and historical hydrographic data. These observations clearly trace the path and transport of the North Icelandic Jet, confirming its importance for the Denmark Strait overflow, and identify its origins along the north slope of Iceland. The project also found that the East Greenland Current forms an offshore branch (which is termed the separated EGC) in the vicinity of the Blosseville Basin (Vage et al. 2013). This has major consequences for the surface and deep circulation. Freshwater is transported into the interior by the separated EGC, which could impact convection in the Iceland Sea. In the deep layer a significant fraction of the overflow water transposes from the Greenland slope to the Iceland slope via the separated EGC. This, together with the North Icelandic Jet, suggests that most of the Denmark Strait overflow water approaches the sill on the eastern side of the strait, in contrast to earlier thinking. A high-resolution regional numerical model indicates that the separated EGC is formed by an instability process triggered by the orientation of the wind field in the vicinity of Greenland orography.

The project also published results related to the general physical oceanography and atmospheric forcing in the Nordic Seas, subpolar North Atlantic, and Arctic Ocean, as summarized below.

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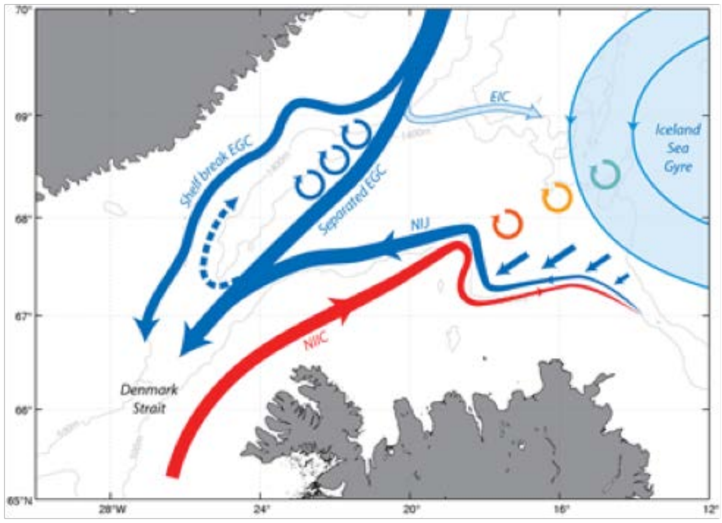

Figure 1. Schematic circulation in the area northeast of the Denmark Strait. The East Greenland Current (EGC) bifurcates north of the Blosseville Basin and the offshore branch joins with the North Icelandic Jet (NIJ) to provide most of the dense water feeding the Denmark Strait Overflow Water plume. The shelfbreak EGC provides the other portion. The separated EGC is believed to be formed by anti-cyclonic eddies that coalesce, with perhaps a wind-driven anti-cyclonic recirculation north of the sill (dashed line). The NIJ represents the lower limb of a local overturning loop: the inflowing North Icelandic Irminger Current – advecting warm Atlantic Water – forms eddies that are cooled by the atmosphere and disintegrate in the Iceland Sea Gyre. The dense waters formed progress back towards the boundary (represented by the short blue arrows) and sinks to form the NIJ. The light blue arrow also indicates a possible pathway for the East Icelandic Current (EIC).

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

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The deep branch of the Atlantic Meridional Overturning Circulation originates in the exchange flow between northern Atlantic and Nordic Seas. Three arteries of dense water flow over the Greenland-Scotland Ridge, dominating the properties of the deep Atlantic. Analysis of 18,864 hydrographic profiles from the three-year NSF-sponsored field program with Seagliders at the Iceland-Faroe Ridge forms the core of this project. Beaird, graduate student under this grant, has carried out much of the work, in collaboration with PIs Rhines and Eriksen. Fer of University 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 a third of the total dense overflow transport). The project's publications have described the circulation and mixing of these dense overflows with unprecedented horizontal resolution, and with Frajka-Williams, spring restratification and biological signals accompanying the spring plankton bloom in the Labrador Sea. The project has used vertical velocity measurements from the gliders to extensively map the turbulent mixing in the overflows for the first time.

Recent results

Beaird completed his Ph.D. (Beaird 2013) in November 2013 and has taken up a post-doctoral fellowship at Woods Hole Oceanographic Institution. During the past year his focus has been mixing in the upper waters at the polar front on the Iceland-Faroe Ridge. This complements the deepwater studies of previous years. Glider sections across the Ridge show intense mixing of low salinity waters originating north of Iceland, and exchanging through mesoscale instability with the warm, northward flowing waters that turn east to form the Faroes Current. The warm water is marked with low oxygen concentration tracing its origins to the deep tropics. Oxygen, θ, and S show the mixing to occur primarily in winter at the time when deep convection penetrates all the way down to the sloping front. Quantitatively, it is a significant contribution to the mixing of warm branch waters as they form the Norwegian Current. The attached figure shows mesoscale intrusions of low salinity/ high oxygen waters south of the polar front, and low oxygen water from the tropics at greater depth.

With Frajka-Williams, seaglider observations of the springtime restratification of the Labrador Sea were analyzed to show how it is that rapid growth of stratification occurs over a short few weeks. Because winter convection homogenizes the water vertically, it is horizontally variable over tens of kilometers, and the collapse of convected columns by lateral interleaving can occur rapidly (Frajka-Williams et al. 2013).

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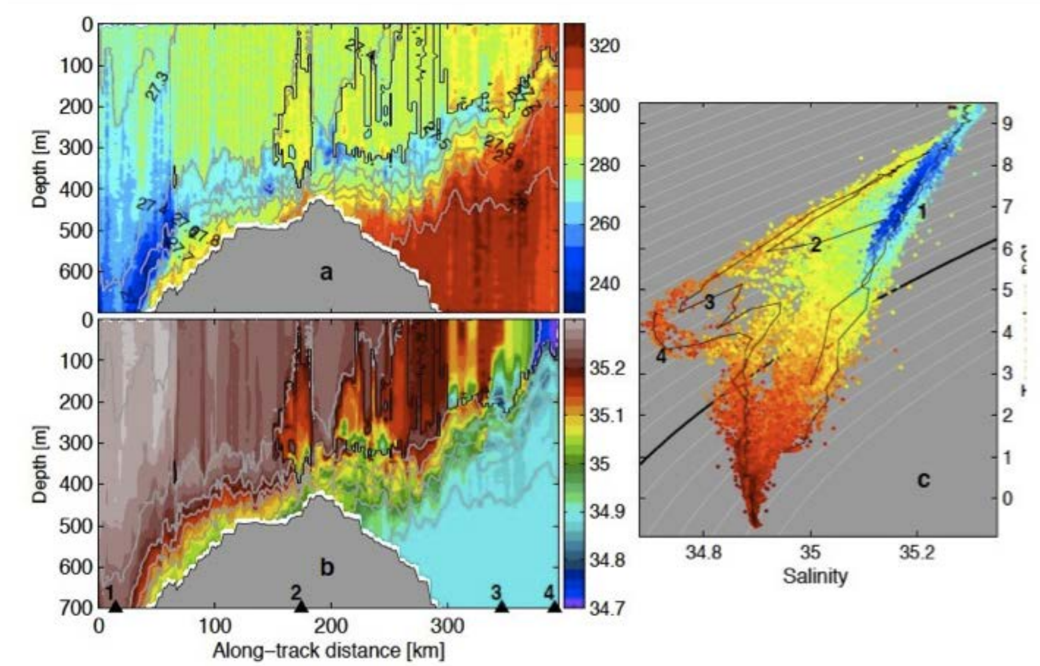

Figure 1. Wintertime convection penetrating down to the polar front. (a) Oxygen concentration (μmol kg—1) on a Seaglider section across the Iceland-Faroe Ridge and polar front 2-19 Dec. 2007; (b) salinity along the section, Isopycnals are contoured in gray; (c) potential temperature-salinity relation for the section, with color showing oxygen concentration (same units and scale as (a)). Example profiles are indicated in black, indicated by the triangles in (b).

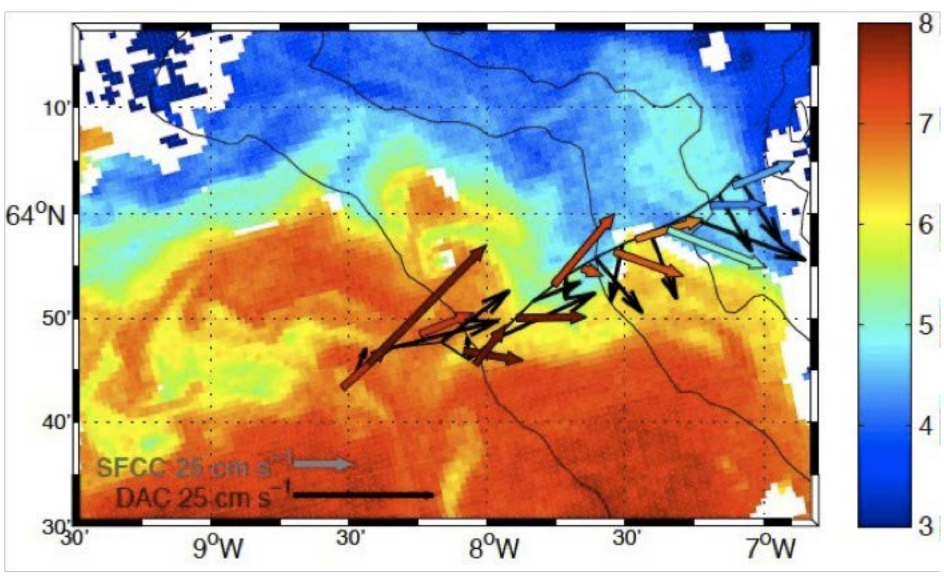

Figure 2. MODIS SST from December 13, 2007 and the depth-average and surface currents from the final 12 dive cycles of the glider section (December 15-19, 2007). The depth-averaged current is shown in black vectors, and the surface current is shown in vectors whose color represents the surface temperature at the location. Note the difference in scales.

Improved Estimates of Atlantic Meridional Circulation from Altimetry with Tracers, Drifters, Gliders, and Argo Floats

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The upper branch of the AMOC has warmed the northern Atlantic to an unprecedented degree since the mid-1990s. 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. There is increasing evidence that this warming feeds back on the atmospheric storm track and blocking, and that it is part of the Atlantic Multidecadal Variability evident in the 130-year climate record (Häkkinen et al. 2011). The northward 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, despite the 20-year weakening 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 (Häkkinen et al. 2013).

A collaborative investigation of the AMOC connections, both deep and shallow, between subtropics and subpolar gyre has been initiated with the HYCOM Atlantic model, with X. Xu and E. Chassignet of Florida State University. The project is analyzing both the warm water pathway through the North Atlantic Current and just below the southward dense AMOC branches flowing from the Greenland-Scotland Ridge and Labrador Sea. The figure below shows a tracer injected at the Denmark Strait at 0.08 degree horizontal resolution and 64 isopycnal layers. Spreading of the overflow water widely occurs outside of the traditional boundary current pathway and dynamical analysis shows its potential vorticity control by the changing topographic environment. This model result coincides with the observed tracers: CFCs, oxygen and Iodine-129.

A separate collaboration with University of Bergen, Norway (T. Eldevik and H. Langehaug) is continuing with the successful funding of their NORTH project (NORthern contraints on the THermohaline circulation). The project is working on the AMOC projected on potential temperature/salinity space using HYCOM simulations and observations, which emphasize the coupling between oceanic meridional transport, watermass transformation through internal mixing and transformation through air-sea freshwater and heat fluxes.

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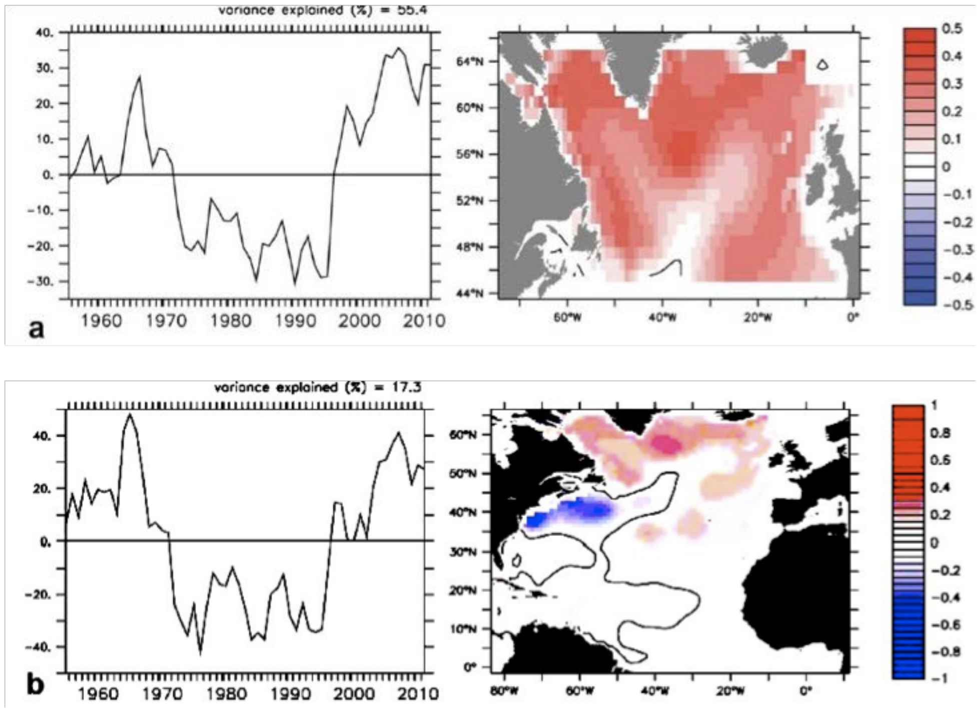

Figure 1. Top: (left) PC1 and (right) EOF1 of the subpolar-only NODC 700 m heat content (limited to 45°N–65°N). Units are 1018 J for PC1 and dimensionless for EOF1. Bottom: (left) PC2 and (right) EOF2 of the whole North Atlantic NODC 700 m heat content for 0–65°N. Units are 1018 J for PC1 and dimensionless for EOF1.

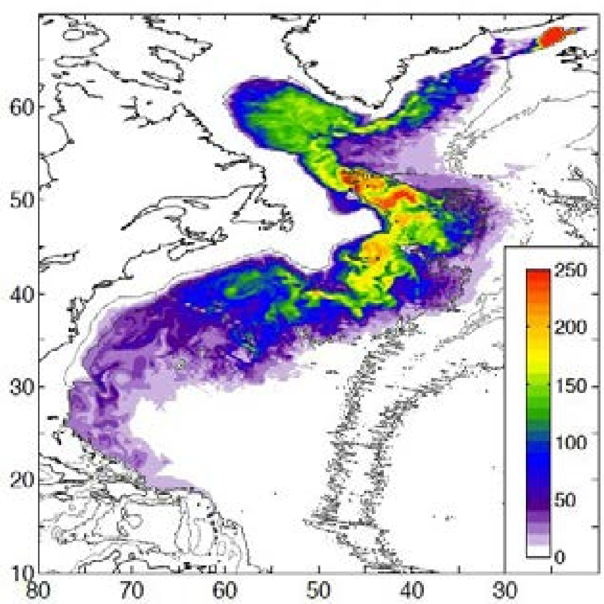

Figure 2. Tracer inventory below potential density σθ = 27.80, 15 years after tracer injection begins at Denmark Strait, 64 layer, 0.08 degree resolution HYCOM simulation. The dense overflow DSOW plume flows dominantly as a narrow boundary current north of 40°N, yet even there it spreads across the entire Labrador Sea and the topographic basins west of the Mid-Atlantic Ridge, forming recirculating gyres which are strikingly evident in observed CFC, oxygen, and Iodine-129 data.

The Norröna Section

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The objective of this program is to continuously monitor the strength and structure of the Atlantic inflow into the Nordic Seas between Scotland, the Faroes and Iceland. This is of fundamental interest because it measures the rate of transformation of North Atlantic water into dense water and thus the strength of the meridional overturning circulation (MOC). We study this exchange by monitoring all water flowing through the area east of Iceland to near the bottom or ~600 m depth using a 75 kHz acoustic Doppler current profiler (ADCP) mounted on the high-seas ferry M/F Norröna.

Starting in March 2008, currents have been measured in the Faroe-Shetland Channel (FSC) and along the Iceland-Faroe Ridge (IFR) on the ferry's weekly round-trips between Iceland and Denmark. The program is ongoing, and as of in November 2013 the Norröna is also equipped with a remotely (Iridium) programmable 12-barrel XBT system enabling us to take concurrent XBT sections at high horizontal resolution. In time, this will lead to improved estimates of heatflux into the Nordic Seas. A first report was published in 2012 (Rossby and Flagg 2012).

Recent results

- The detided average transports (to the north) across the two sections are 4.1 ± 0.1 Sv (10^6 m^2s^{-1}) through the FSC and 4.4 ± 0.25 Sv across the IFR (this excludes ~1.6 Sv circulating around the Faroes). The total net inflow into the Nordic Seas is about 9.3 ± 0.3 Sv (8.5 + 0.8 Sv west of Iceland) (Jónsson and Valdimarsson 2005).
- Using hydrographic data from the ICES database we construct a mean temperature field, which when advected by the mean flow north sums to 176 TW. The total net heat supply available the Nordic Seas thus becomes about 176 TW plus 22 TW west of Iceland (Jónsson and Valdimarsson 2005), less 27 TW outflow through DS (4 Sv at 1.7°C) (Dickson et al. 2008), totaling 171 TW northward. The uncertainty of this number due to the 0.3 Sv uncertainty in inflow is probably at the 10% level. Segtnan et al. (2011) estimate the total heat loss to the atmosphere in the Nordic Seas to be 198 TW, which can be compared with this result.

Online data

http://po.msrc.sunysb.edu/Norrona/

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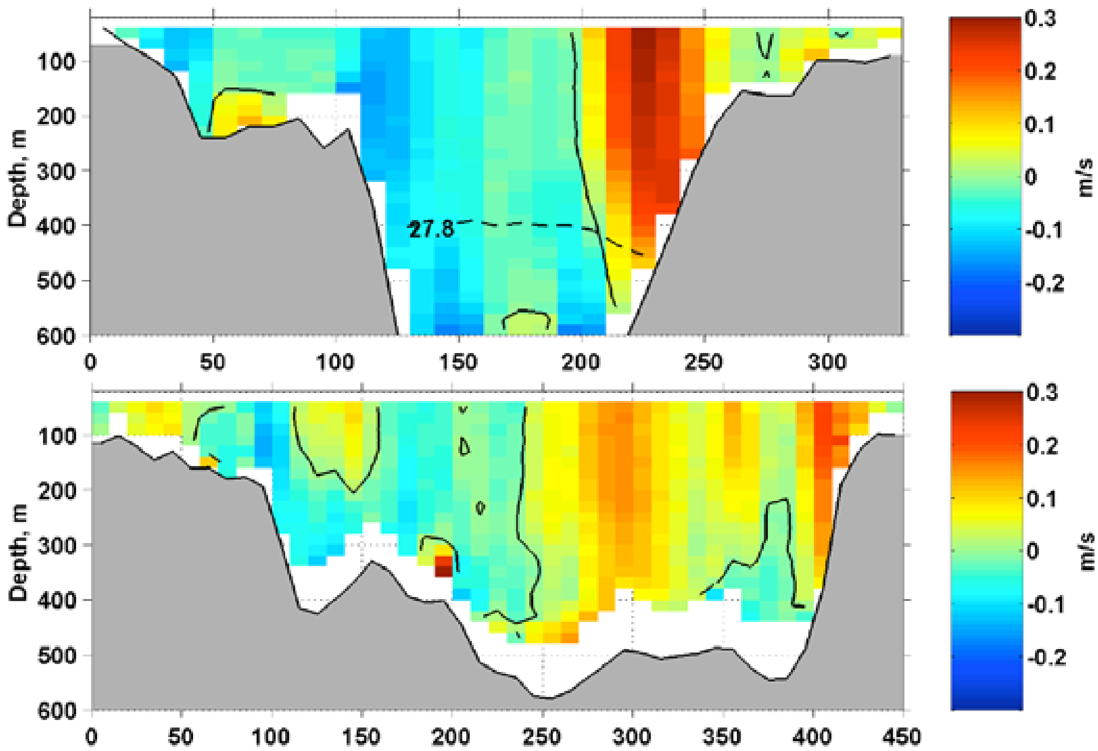

Figure 1. The top panel shows mean detided velocity (positive towards the Nordic Seas) in the Faroe-Shetland Channel. Distance in km from the Faroes (left) to the Scotland shelf (right). The bottom panel shows the corresponding velocity field between Iceland to the left and the Faroes to the right (distance in km from Iceland).

SNACS: Subpolar North Atlantic Cross-Sections

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This proposal describes a plan to establish a new eddy-resolving velocity observatory in the subpolar region of the North Atlantic Ocean by installing vessel-mounted Acoustic Doppler Current Profilers (ADCPs) on two cargo vessels in regular service between Iceland and North America. When fully operational, this observatory will provide up to 48 high-resolution velocity transects per year with deep-reaching 38 kHz ADCPs to a depth of 1200 m through the western subpolar region, and along the continental shelves of maritime Canada and New England with high-resolution 150 kHz ADCPs. Additionally, automated expendable bathythermograph (XBT) launch systems will be installed on one vessel, as well as on an existing velocity observatory on the cargo vessel Nuka Arctica that runs between Denmark and Greenland, to provide simultaneous temperature transects across key areas of the subpolar region. Software and communications systems will be developed to make processed ADCP data from volunteer observing ships publically available in near real-time. Scientific objectives are focused on elucidating relationships between transport, eddy variability, and changing atmospheric forcing on seasonal-to-interannual time scales, for three areas of the subpolar region: the warm Irminger Current and associated eddies, the high-contrast Labrador and North Atlantic Currents at the Northwest Corner, and the complex region where Labrador Sea and nutrient-rich St. Lawrence River waters impact the slope sea and continental shelf.

Background and summary

In spite of its prominence in the climate system, the view of the mean circulation in the subpolar region, and its variability on seasonal and longer time scales, is an overly smoothed one due to the inability of most observing techniques to resolve the dominant eddy scales at high latitudes set by the <15 km deformation radius (Stammer 1997; Chelton et al. 1998). Today, well-proven techniques using vessel-mounted acoustic doppler current profilers (ADCPs) allow for measurements of velocity directly along ship tracks, yielding high-resolution (1-3 km), accurate (0.01 - 0.02 m s^{-1}) sections of both components of motion from the sea surface to depths greater than 1000 m. Ensembles of sections collected on repeated transects provide self-defining frameworks for quantifying both the mean flow and its variability in the horizontal and the vertical over many years (e.g., Knutsen et al. 2005; Rossby et al. 2010; Rousset and Beal 2010).

This project will expand the coverage of existing and planned observing networks across the subploar region with particular focus on fronts and mesoscale processes. The ADCP with its high accuracy and high-resolution scans will bring an expanded capability to the study of physical and biogeochemical oceanographic processes. The combination of velocity and temperature along both the AX02 and AX01 XBT lines will provide a solid foundation for basin-wide studies of currents and their response to seasonal to interannual variations in winds and buoyancy fluxes. These ADCP lines will complement the Norröna ADCP/XBT operation between Scotland, the Faroes and Iceland, and the on-going Norwegian operated Nuka Arctica section between Denmark and Greenland along ~60°N. They will also complement the first phase of OSNAP with its focus on AMOC transports through the subpolar region. The majority of the resources requested here will go toward establishing the data collection system and toward making the processed data available immediately to the larger scientific community.

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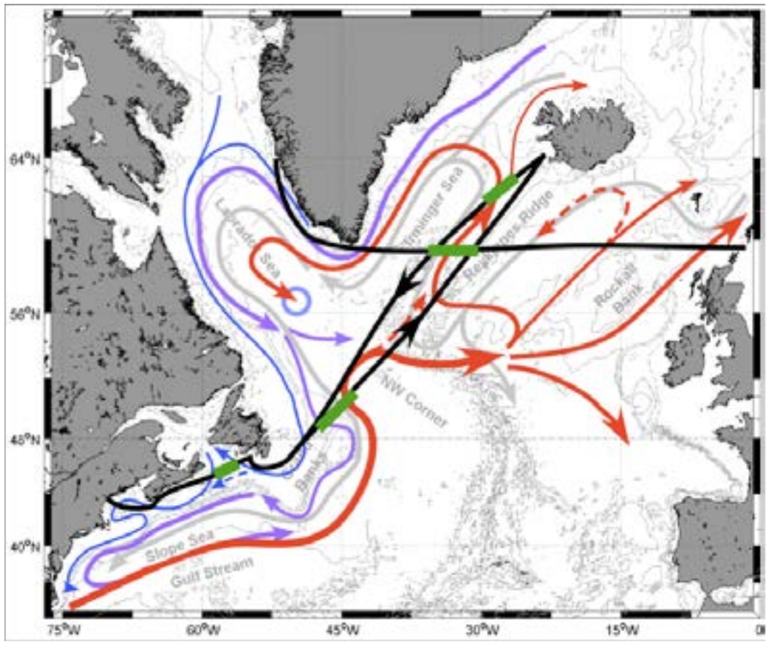

Figure 1. Schematic diagram of currents in the SPR together with the Eimskip and *Nuka Arctica* routes (black lines). The red line indicates poleward flow of warm water, the purple line flow of fresh water from the Arctic, and grey lines that of deep dense overflow water. The green bars indicate the locations of XBT sections collected as part of the proposed program. The north-south black lines show how the vessels take advantage of the Irminger Current on northbound transits and pass through the central basin on southbound transits.

Transport Pathways in the North Atlantic: Searching for Throughput

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

Recent results

One species of great scientific and economic interest is the American eel. This catadromous fish, which lives in freshwaters as an adult, but spawns in the ocean, undertakes a remarkable migration from their freshwater habitats along the east coast of North America to the Sargasso Sea, where they spawn planktonic eggs and die. The eggs then develop into small and vulnerable larvae. To complete their life cycle, eel larvae have to reach coastal waters along the North American coast within their first year of life, and to do so, must cross several oceanic transport barriers including the Gulf Stream and the continental slope/shelf break front of the Middle or South Atlantic Bight.

Although the focus of several studies, many details of the American eel larvae journey remain a mystery. Can eel larvae simply rely on the oceanic currents to bring them from the spawning grounds to the coast? Or must they actively swim to complete their journey? The coupled biological-physical model, which melds taxon-specific characteristics and behaviors with the high-resolution oceanographic FLAME model, has proven useful in investigating these questions. Because the swimming and navigation strategy of American eel larvae is not known, apart from their diel vertical migrations, the project tested a variety of possible lateral swimming behaviors – passive drift, random-walk swimming, navigation using gradients in the physical characteristics of ocean water, and directional swimming using magnetic fields or similar cues – in order to explore which strategy can significantly aid American eel larvae success in completing their journey from the Sargasso Sea to coastal nursery habitats. The analyses suggest that passive drift and random-walk swimming result in extremely small percentages of successful larvae. While it cannot definitively say that such percentages are insufficient for population replenishment, the project clearly shows that directional swimming substantially improves the chances of survival for American eel larvae (Figure 1). Active directional swimming is important for detraining from the Gulf Stream, crossing the slope, and reaching the coast.

Several factors in the analysis could be indicative of a natural selection process. First, eel larva, with even slightly above average swim ability, have a much better chance of survival compared to the slow-swimming larva. Second, for the average larvae with directional swimming abilities, it takes about one year to reach the coast, which agrees with the biological development time of American eel larva. The model also naturally picks the northwestern direction as the preferential swimming strategy, suggesting that it is possible that American eel larvae have evolved to swim primarily towards the coast. The last result is interesting as it could explain why American eel larvae travel to the North American coast, whereas European eel larvae, which also spawn in the Sargasso Sea but presumably do not pick the northwest swimming direction (or perhaps are weaker swimmers or do not swim at all during early development stages), get advected eastward by the oceanic currents and end up on the European coast.

Future work will investigate the potential influence of the changes in the North Atlantic oceanic circulation on the American eel population variability over the last two decades.

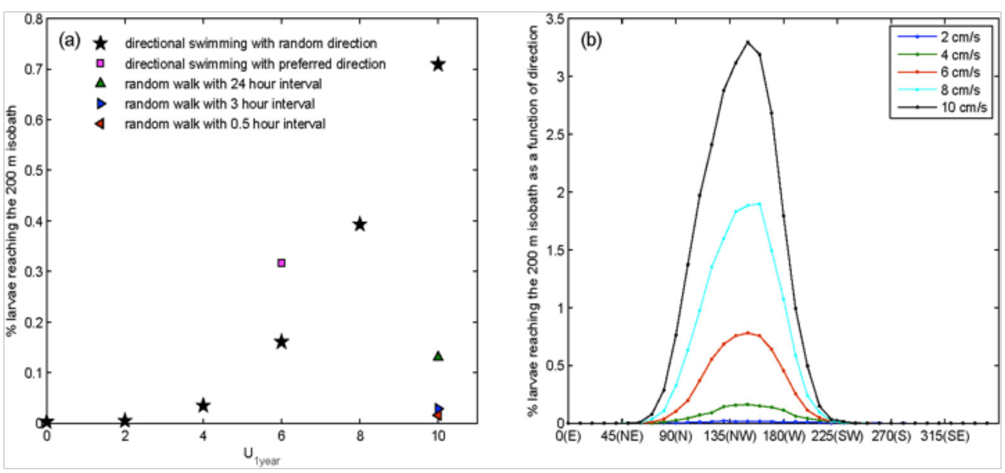

Figure 1. (a) Success rate (in percent) of simulated larvae crossing the 200 m isobath for different swimming strategies and different swimming speeds. Each model run covers 1995-1999 and is based on ≥ 1 million simulated particles released in the Sargasso Sea in Feb-Apr of each year. Directional swimming simulations include mortality (at M=3.8/year); random walk simulations do not include mortality. (b) For directional swimming simulations with random direction (corresponding to black stars in panel (a)), probability to cross the 200 m isobath as a function of swimming direction for different swimming speeds U_{1year}. In this model run, the project randomly assigned the larvae an initial direction and then had them maintain it for the entire journey.

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 (AMO). 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 this 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

One of the important issues in AMOC research is the potential role of North Atlantic sea surface temperature (SST) anomalies in affecting precipitation extremes, such as droughts and floods, over continental regions surrounding the Atlantic Ocean. In particular, it is believed that some of the long-term precipitation trends in this region may be attributable to regional modes of SST variability such as the AMO. A useful tool for studying this attribution problem are regional climate models because they can specify different lateral and surface boundary conditions to represent the impact of different regional forcings.

The project has carried out a regional attribution study for the continental US domain using the WRF model at 27km horizontal resolution to address the role of SST anomalies (SSTAs) in the Atlantic and eastern Pacific and high-frequency atmospheric variability from the Pacific during the 1993 and 2008 Midwest (Patricola et al. 2013). The findings show that the SSTAs insignificantly modulate Midwest rainfall during the 1993 flood, but enhance precipitation during the 2008 peak flood by strengthening the southern portion of the Great Plains low-level jet, enhancing moisture transport from the Gulf of Mexico into the Midwest (Figure 1). The study suggests that while North Atlantic SST strongly controls Midwest decadal drought and pluvial periods, it plays a minimal or secondary role in modulating extreme flood events lasting weeks to months. A negative Pacific/North American (PNA) teleconnection marked the peak of both floods, suggesting a link between extreme Midwest warm season rainfall and high-frequency PNA variations. Simulations that apply a 10-day low-pass filter to the western lateral boundary condition indicate that interactions between the eddy and time-mean flow played a significant, but counterintuitive role, during the 1993 flood. Although above normal Pacific cyclone activity was observed to trigger heavy Midwest precipitation, the synoptic eddies also indirectly influenced rainfall by modifying the time-mean circulation. The simulations also show that eddies from the Pacific dampened the positive rainfall anomalies by weakening vertically integrated moisture transport and upper level divergence anomalies over the Midwest.

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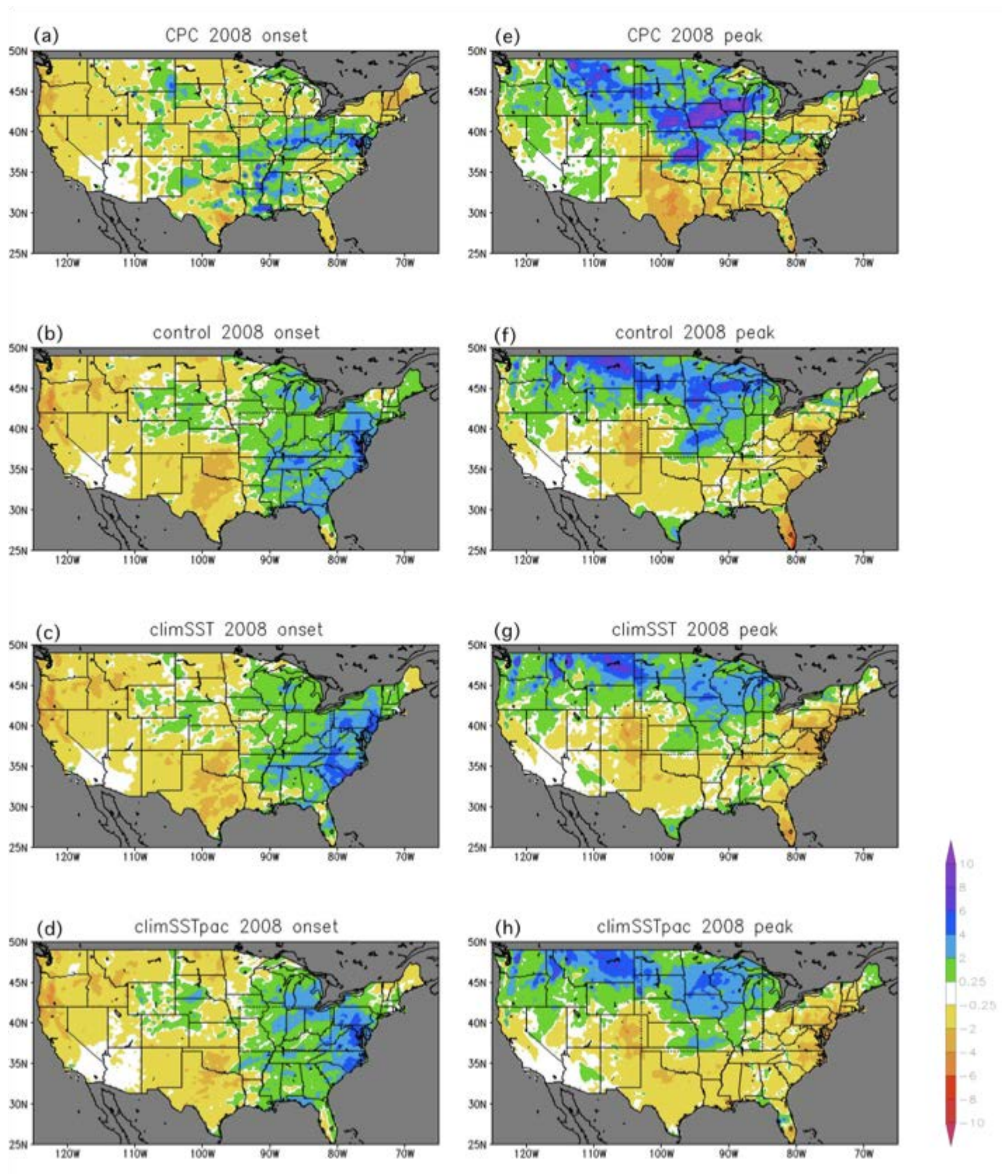

Figure 1. Simulation of the 2008 Midwest floods using WRF. Precipitation anomaly (mm/day) relative to the corresponding 1981-2000 base period during the 2008 onset (early May) and peak (late May to mid-June) periods, respectively, from the (a, e) CPC observational dataset and ensemble mean of the (b, f) control WRF run with observed b.c., (c, g) climatological SST run, and (d, h) climatological SST + pacific SSTA run. Note that both climSST and climSSTpac produce only weak Midwest rainfall anomalies, indicating that Atlantic and eastern Pacific SST anomalies together significantly enhance the peak rainfall. (Regions outside the continental US are masked grey.)

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

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Recent observations reveal accelerated melting of the Greenland Ice Sheet (GrIS). Projections of future effects suggest continuing ice loss at increasing rates for business-as-usual anthropogenic greenhouse gas emissions scenarios. Additional meltwater fluxes into the surrounding North Atlantic ocean will increase the buoyancy of surface waters, which may reduce their rates of convection, subduction, and sinking to the deep ocean and hence slow down the Atlantic Meridional Overturning Circulation (AMOC). Detailed estimates of the GrIS mass balance show that it is influenced by North Atlantic climate variability, suggesting a possible feedback between the GrIS and the AMOC. However, most comprehensive climate models currently do not include interactive ice sheets. Thus projections of future climate change performed with these models (including CMIP5) do not consider impacts of GrIS melting on AMOC variability although it is well known that the AMOC is sensitive to freshwater fluxes to the North Atlantic. The probabilities of AMOC reduction and shutdown for a given greenhouse gas emission scenario are therefore poorly known. Moreover, previous studies of AMOC internal variability and predictability did not consider feedbacks between the GrIS and the AMOC.

The project plans to organize a model intercomparison project, involving the major climate modeling centers around the world, aimed at quantifying the effects of GrIS mass balance changes on current and future AMOC variability and predictability including uncertainty estimates. Realistic meltwater scenarios will be developed based on a new approximation of GrIS surface mass balance changes. The meltwater will be distributed to the ocean along the Greenland coast using a realistic runoff scheme. The range of meltwater scenarios will consider uncertainties associated with estimating future mass balance changes. Different state-of-the-science climate models will be forced with these scenarios in addition to standard radiative forcing in order to quantify the AMOC response to warming and meltwater input as well as the uncertainty of model AMOC sensitivities to the imposed forcings. Probabilistic AMOC projections will be computed based on the multi-model ensemble. Simulations with an interactive scheme of GrIS mass balance changes will be used to quantify the effect of ice sheet - ocean interactions on AMOC variability and predictability on decadal to centennial time scales. The model experiments will be carefully analyzed in order to understand responses and model differences. The probability of an AMOC shutdown in the coming two centuries will be quantified.

The Nuka Arctica Program

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The objective of this program is to continuously monitor the poleward flow between Scotland and Greenland. During the years 1999-2002 a 150 kHz ADCP mounted in the hull of the container vessel Nuka Arctica measured currents along the vessel's route between Scotland and Cape Farewell. An earlier paper by Knutsen et al. (2005) showed that the mean flow in the central northeast Atlantic was strongly constrained by the topography of the Reykjanes Ridge. A reanalysis of this earlier dataset has been combined with the AVISO altimetric dataset to examine the space-time variability of poleward transport. The high-resolution scans of currents in the top 400 m show that the Reykjanes Ridge serves as a very effective separator of flow towards the Nordic and Labrador Seas, respectively. Whereas the Labrador Sea branch exhibits two mean flows to the north on the western slope of the Reykjanes Ridge, the eastern branch flows north in roughly equal amounts over the deep Maury channel and east of Hatton Bank including the Slope Current. There is also a well-defined southward flow along the eastern slope of the Reykjanes Ridge. The main point here is that the high-resolution repeat scans reveal a previously unresolved fine structure in the mean flow. The satellite altimetric sea surface height (SSH) data show good overall agreement with geostrophically determined sea level difference from the repeat ADCP sections (1999-2002). In addition, the altimetric data show that variations in poleward flow west and east of the Reykjanes Ridge are strongly anticorrelated (Chafik et al. 2014).

The Nuka Arctica ADCP program was restarted in fall 2012, now with a 75 kHz ADCP that reaches to about 800 m. XBTs are taken on a seasonal basis. The ship also monitors surface water properties with a thermosalinograph.

Data are not yet available online, but plans are underway for an online data server. The older 150 kHz dataset is available from the PIs.

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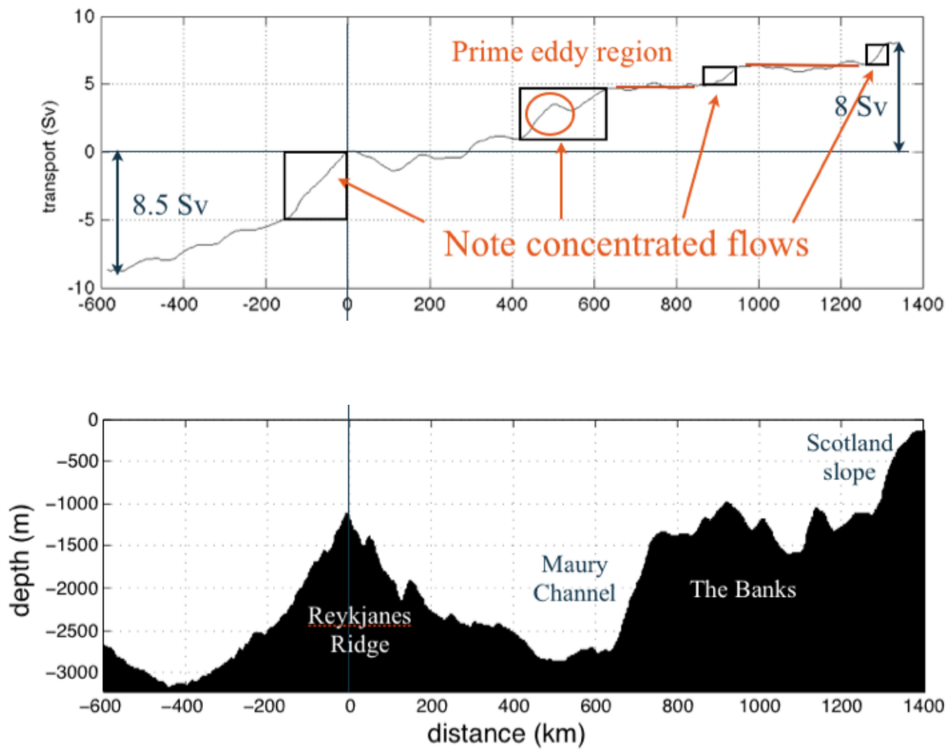

Figure 1. This figure, adapted from Chafik et al. (2014), shows poleward flow across 60°N from just east of the East Greenland Current to the Scotland Slope. Note the strong flow north west of the Reykanes Ridge, most of which is thought to continue towards the Labrador Sea. The flow north east of the ridge is broken up into several branches, with roughly half of the flow north in the Maury Channel, and the remainder channeled through and by the complex Banks topography and along the Scotland Slope. A major objective for restarting this program is to determine the stability of these flow patterns, both spatially and temporally.

An OceanScope Program

SCOR[1] — IAPSO[2] Working Group #133
[1]Scientific Committee on Oceanic Research
[2]International Association for the Physical Sciences of the Ocean

Over the last several decades oceanographers of all disciplines have noted significant changes taking place in the marine environment: steady increases in upper ocean temperature, major shifts in plankton distributions, increases in dissolved CO_2 and acidity and possible circulation changes. Despite the growing sense of urgency, at the OceanObs'09 conference in Venice, Italy in September 2009 (see http://www.oceanobs09.net/), there was general agreement that the ocean, especially the water column, continues to be severely under-sampled. Calls for new and better sensors and measurement strategies, along with closer coordination among the many different ongoing ocean-observing programs, were strong recurring themes. These led to a final post-conference synthesis Framework for Ocean Observing.

Prior to OceanObs'09, a proposal was submitted to SCOR to establish a science-industry working group to develop a framework for an operational partnership between the ocean observing community and the global maritime industries. SCOR and IAPSO co-sponsored working group #133, hereafter called OceanScope, to develop an implementation plan to monitor the global ocean water column on a long-term continuing basis. The idea is powerful, but very simple.

Commercial ships have a strong presence on the high seas and offer society a feasible and cost-effective opportunity to contribute to solving this observational deficiency. Building upon the success of elements in the present global ocean observing system (GOOS) and pilot research projects aboard selected commercial vessels, OceanScope proposes a formal partnership with commercial vessel owners and operators to enable systematic and sustained observation of the structure and dynamics of the ocean water column enabling physical, chemical, and biological processes to be studied simultaneously across all the interconnected ocean basins. Critical processes could thereby be sampled on time and space scales impossible to sample by research vessels, floats, drifters, AUVs, ROVs, or satellites.

Specifically, OceanScope proposes to develop and implement techniques including acoustic and optical remote sensing, expendable probes and towed systems to monitor the entire oceanic water column, and to do so not only with respect to ocean physics, but also ocean chemistry and biology - all optimized for automated use on merchant marine vessels repeatedly transecting critical oceanic domains. Only a fully integrated and coordinated approach, as envisioned in OceanScope, can enable the standardized methodologies and technologies essential for operational reliability and data continuity, provide the economies of scale essential to reduce installation, maintenance, and operational costs, and stimulate the development of improved observational technologies. Installation costs are radically reduced with new builds. Industry partners have encouraged us to envision commercial vessels "ready-built" to join the OceanScope fleet. A fleet of instrumented commercial vessels regularly transecting the same routes would be a major addition to the international GOOS, building upon and complementing programs such as Argo and the global drifter program. Synergistic deployment would markedly increase the value of programs - like the integrated carbon observation system (ICOS) and the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) that operates the continuous plankton recorder (CPR) program - in that their biogeochemical observations would be made within a fully characterized physical context.

OceanScope would be implemented in phases. Phase one would extend and integrate today's OceanScope capable vessels (ADCP, auto-XBT, flow through, and pCO2 equipped) into a fleet of 20-instrumented vessels operating in the North Atlantic Ocean (see map of proposed routes below). Such a test bed phase will not only focus attention upon a system of major importance to global climate dynamics (e.g. the meridional overturning circulation), but also explore how best to further existing scientific collaborations with the maritime industry. While vessels would at first rely upon existing technology (or small improvements thereof), marine vessel-optimized and standardized instrumentation would be installed across the fleet of OceanScope vessels, as it becomes available. Being able to measure currents, temperature, and other properties across a range of latitudes will greatly expand our knowledge of transport processes throughout the North Atlantic. Building upon the success of the North Atlantic test bed, OceanScope would then gradually expand throughout the world ocean.

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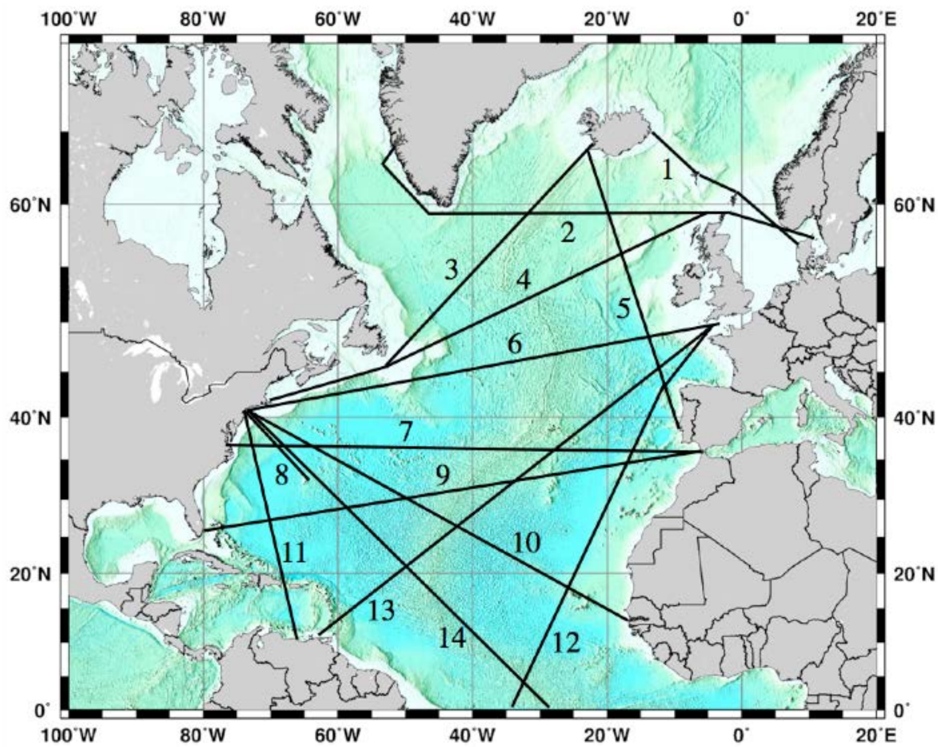

Figure 1. Map of proposed routes in initial North Atlantic test bed phase. Many of these are already partially in service. ADCPs are in regular service along 1, 2, 8, and 11. CPRs are towed along 2 and 3 and others not shown. XBTs are taken along 1, 2, 3, 8, 9, 11, 14, and thermosalinographs and/or CO2 on many routes. The next step is to integrate these diverse activities into a greater whole so that storage and transport of mass, heat, gases and other properties can be tracked effectively. All instrumentation would operate autonomously without at-sea technical supervision.

MOVE: Meridional Overturning Variability Experiment

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The objective of this project is to maintain an operational observing system to continuously sample the strength of the lower branch of the Atlantic meridional overturning circulation (AMOC) at 16°N. The US portion of the system extends from the western boundary to the mid-Atlantic ridge. In recent years, German partners have operated a companion mooring near the Cape Verde Islands. The MOVE time series started in 2000, and has now returned over 13 years of data.

In April - May 2013, all three MOVE moorings were recovered and re-deployed as part of the routine service of these platforms, using the German vessel Meteor. The service interval for the moorings is now approximately two years, to increase operational efficiencies. The figure below shows the strength of the AMOC computed with these recent MOVE mooring data. In addition, two PIES bottom instruments were added to the two existing ones during the Meteor cruise. Service intervals for the PIES are now targeted to be four years, with duplicate instruments overlapping in two-year increments. The previous duplicate instruments had been recovered in 2012. The goal of these increased PIES mission lengths and the duplication of instruments is to improve the low-frequency signals in the bottom pressure data, which serve as reference levels for the geostrophic velocities. Processing of the first overlapping PIES data (2010-12) is ongoing.

All MOVE platforms (moorings and PIES) are now equipped with acoustic data upload capability, i.e. subsets of the data are transferred into an acoustic modem that can be read out from e.g., a ship or a glider. In October 2013, this acoustic data path was exercised for the first time from the US vessel Ronald H. Brown, and data from all platforms except the two older PIES was retrieved.

Regretfully, MOVE was not represented at the 2013 AMOC meeting due to conflicting fieldwork requirements. However, their participation is anticipated at the 2014 event.

MOVE data have been used in relevant sections of the State of the Climate reports for 2011 and 2012 (Baringer et al. 2012, 2013), as well as in an article by Srokosz et al. (2012). Similar use is anticipated in the upcoming IPCC 5th assessment report.

The MOVE website has recently been updated and contains a list of publications, as well as links to data available for download:
http://mooring.ucsd.edu/projects/move/move_intro.html

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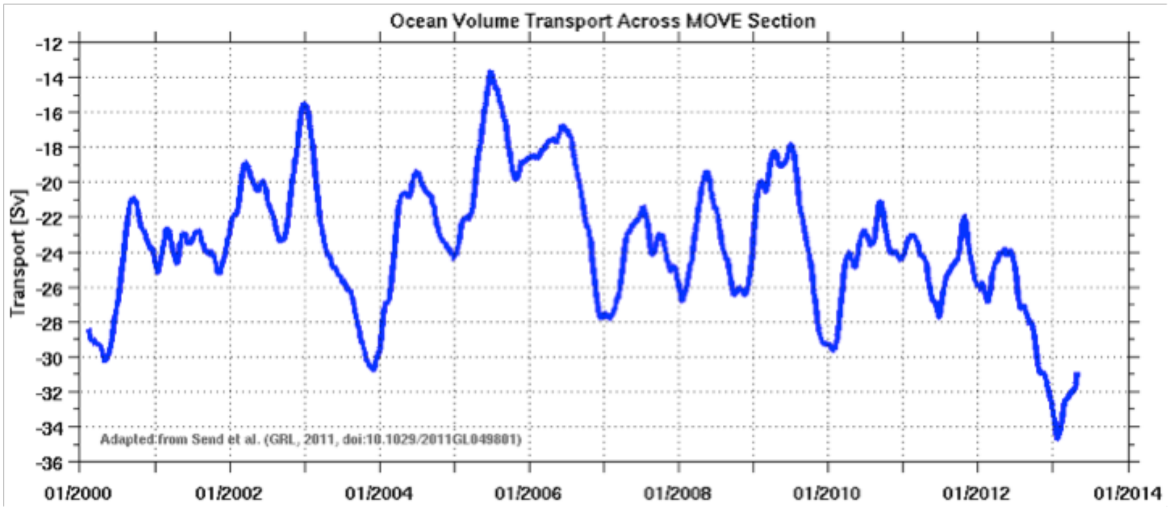

Figure 1. MOVE water volume transports in the layer 1200 to 4950 m, computed as the sum of two components: the "boundary" and the "internal" component. The figure is based on a similar one by Send et al. (2011), with minor updates to processing and extension of the data records to include the spring 2013 recoveries.

Satellite Monitoring of the Present-Day Evolution of the Atlantic Meridional Overturning Circulation

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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). The 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

- Analysis of the sea level budget and its contributions from ice sheet melt water freshening and steric sea level using contemporary geodetic observations (altimetry, GRACE) and Argo, indicated that contrary to the recent published results, that the budget is not closed primarily limited by the present knowledge to model the seafloor uplift due to the continuing glacial isostatic adjustment (GIA) process. Presented here is the first inversion separating the present-day mass component of the sea level rise (PMC) and seafloor uplift, resulting in a reduced global PMC estimate at +2.23 mm yr^{-1}, 2003–2012 (Figure 1, left panel).

- The project finds evidence of non-negligible effect of abyss (>1000 m) contributions of the steric sea level, which is limited by the depth and sampling of the hydrographic (XBT/Argo) measurements, in particular in the Antarctic sector of the AMOC.
- The project has generated decadal (1996–2010) surface and subsurface currents using multiple radar altimetry (ERS-1/-2 and ENVISAT) and XBT/Argo hydrography data, 1996–2010, showing the present-day evolution of the AMOC. Data product will be available to the scientific community in the near future.
- The project computed the trends of the geostrophic surface/subsurface current velocities and decomposed them into zonal and meridional components (Fig. 1, right panel shows the meridional component). The Labrador Current (LC) and East Greenland current (EGC) shows the trends at about –0.1 cm/s yr^{-1}. The subarctic ocean (East of Greenland and northwest of Scandinavian Peninsula) shows a decreasing trend of as large as –0.5 cm/s yr^{-1}. The North Atlantic Current (NAC) extending from the Gulf Stream shows a positive trend of around 0.2 cm/s yr^{-1}. It is inconclusive to imply the definitive changes of the evolution of the AMOC based the short record of this dataset. More analysis and additional data are needed.

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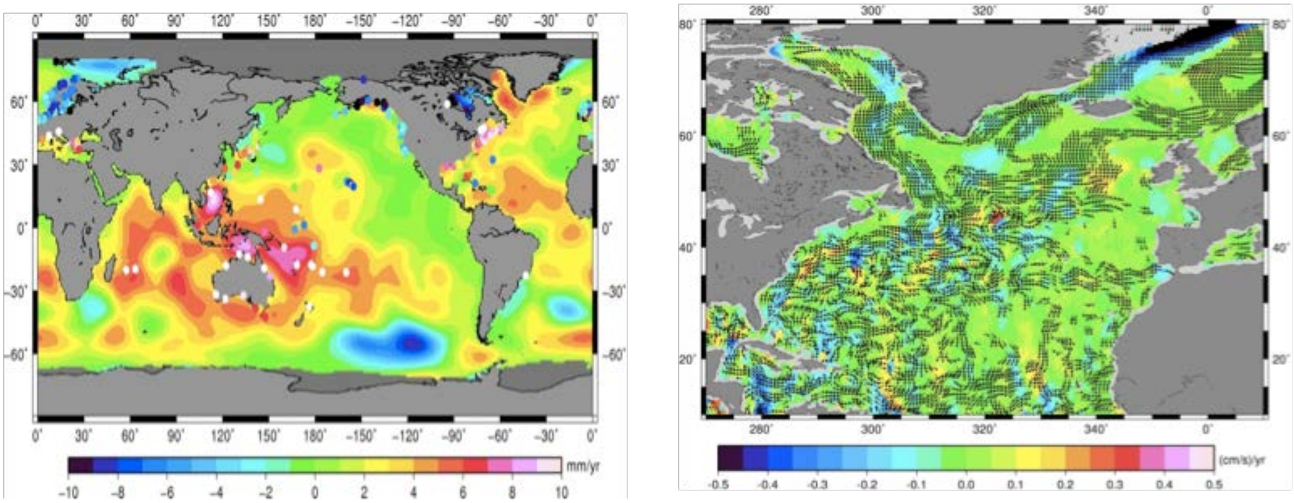

Figure 1. *Left:* estimated present-day ocean mass trend, 2003–2012, +2.23 mm yr-1 in an inversion to separate seafloor GIA uplift (estimated at –0.49 mm yr^{-1}), combining Envisat/Jason-1/2, Argo and GRACE data. *Right:* Trend of meridional surface current velocity (zonal and subsurface current velocity trends not shown), from multiple radar altimetry and XBT/Argo data, 1996–2010, covering the North Atlantic region. Subarctic ocean current velocity rate shows a slow down magnitude of as much as –0.5 cm/s yr^{-1}, in general, the trends are between –0.1 to –0.3 cm/s yr^{-1}. In the mid-latitude, zonal geostrophic current rates shows a speedup of around +0.3 cm/s yr^{-1}.

Forced Transients in Water Mass Transformation and the Meridional Overturning

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

Recent results

There have been two major activities in the past year:

1. An idealized numerical model and a conceptual theoretical model of the Arctic Ocean and its exchange with the Nordic Seas have been developed. The Arctic models produce many realistic features of the Arctic circulation and exchange with the Nordic Seas despite their simple configuration and forcing. It is found that lateral eddy fluxes from the boundary currents in the Arctic are balanced by vertical diffusion to form and maintain the halocline. The resulting density gradients force a cyclonic circulation of Atlantic water around the Arctic basin. The theoretical model compares well with the eddy resolving numerical model and makes clear the parameter dependence of the solutions (Figure 1). This steady-forced model is now being used as a starting point to understand how forced transients propagate through the system.

2. Simple dynamical systems models of forced transients in a convective basin have been developed and comparisons with an eddy resolving numerical model are being carried out. This is in collaboration with Y. Yasuda, a graduate student at the University of Tokyo and a fellow of the WHOI Geophysical Fluid Dynamics summer school in 2013. The response of a convective basin to transients in precipitation depends primarily on the non-dimensional frequency of the forcing, its amplitude, and how close the solution lies to a critical value of precipitation that marks transition between thermal and haline modes. Preliminary comparisons between the theoretical model and eddy resolving numerical models suggest that there is qualitative agreement, but the magnitude of the response in the dynamical systems model appears to be lower than that in the numerical model. Work is now underway to understand the causes of this disagreement. The ocean response to transients forced by a step-change in forcing is now being explored.

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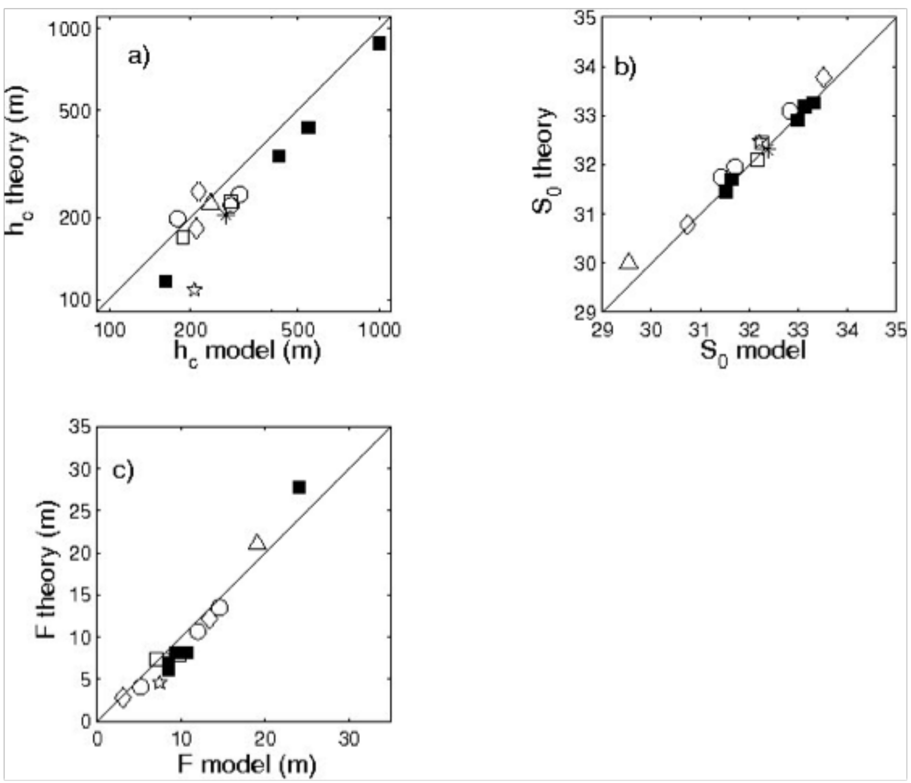

Figure 1. A favorable comparison between theory and an eddy resolving numerical model for a) halocline depth; b) surface salinity; c) freshwater content in the halocline. Each symbol represents a different model calculation in which environmental parameters have been varied. Realistic halocline properties are produced for vertical diffusion coefficients of 10^{-5} to 10^{-6} $m^2\ s^{-1}$, in line with observational estimates of diapycnal mixing in the Arctic halocline.

Glacier-Ocean Coupling in a Large East Greenland Fjord

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Ice sheet—ocean interactions have emerged as a sizable contributor to ice sheet variability in both hemispheres with major impacts on sea level rise and freshening of ocean waters. In this project, we investigate ice sheet ocean interactions in one major glacial fjord, in southeast Greenland, and how large-scale changes in the North Atlantic Ocean and regional atmosphere are linked to dynamic changes of the Greenland Ice Sheet. One direct impact of ocean and atmospheric warming on the ice sheet is the increase in submarine melting of glaciers, which can lead glacier instability. Prior results, published in five papers (see previous US AMOC reports), have shown that fjords are filled with warm Atlantic waters beneath cold polar waters. The Atlantic waters contain enough heat to melt substantial amounts of ice and the limiting factor is the exchange of heat across the ocean/ice boundary layer. The results indicate that fjords are dynamic environments whose circulation is strongly governed by a combination of shelf/fjord exchanges and buoyancy input from the glacier. On longer timescales, a paleo-reconstruction from a major glacial fjord shows that glacier retreat is strongly tied to oceanic variability.

Over this last year, the project investigated the link between changes in the North Atlantic Ocean and atmosphere over the last 100 years and variability of the Greenland Ice Sheet (Figure 1, Straneo and Heimbach 2013). Results show that at present the North Atlantic Ocean and atmosphere are the warmest on the historical record, even warmer than the previous warmest phase in the 1930s. This warming coincides with evidence of dynamic ice loss from Greenland. It raises questions about the role of AMOC and poleward heat transport changes in driving ice loss from the Greenland Ice Sheet.

On the local scale, fjord data has been used to show that during winter the fjord circulation and properties – and thus the submarine melt rate – is largely controlled by passing synoptic wind-events, which drive rapid fjord/shelf exchange and can flush the fjord within days (Figure 2). This means that variability on the shelf is rapidly communicated to the glacier margins.

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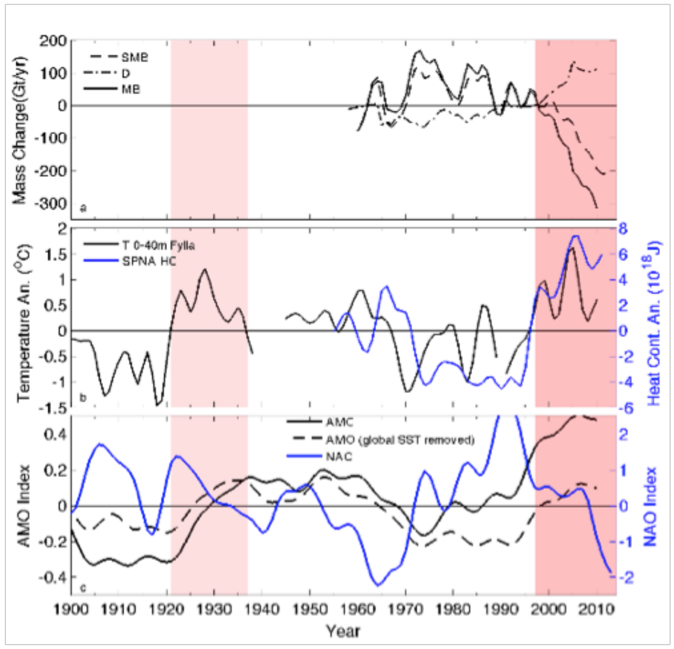

Figure 1. Retreat of Greenland's outlet glaciers is occurring at a time when the waters of the subpolar North Atlantic are the warmest on record (Straneo and Heimbach 2013). All time series have been extended to 2010 and 5-year low-pass filtered, with the mean with respect to the period shown removed. Darker shaded box indicates the period of recent glacier acceleration, lighter shaded box a similarly warm period in the 1930s with evidence for glacier retreat of comparable magnitude. *Top:* Mass balance (MB), surface mass balance (SMB) and ice discharge (D) anomalies in Gt/yr, based on (Bamber et al. 2012, van den Broeke et al. 2009). *Middle:* Mean temperature anomaly of the upper 40 m at Fylla Bank (W Greenland; Andresen et al. 2012) and heat content anomaly of the SPNA's upper 700 m (Hakkinen et al. 2013, *JGR*). *Lower:* Atlantic Multidecadal Oscillation (AMO) index anomalies with and without the global SST trend removed (Enfield et al. 2001, Trenberth et al. 2005), and NAO winter index (Hurrell 1995).

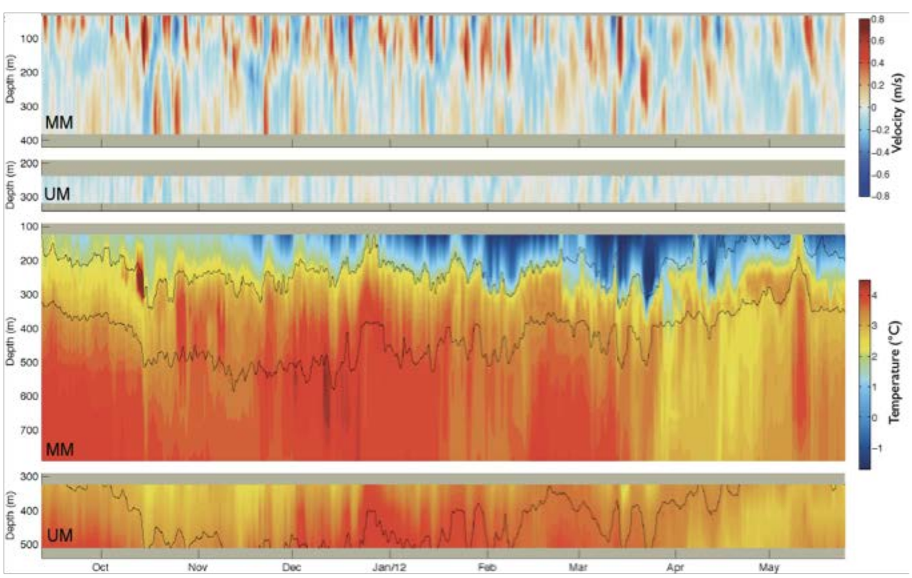

Figure 2. Along-fjord velocity and temperature observations from two moorings deployed in Sermilik Fjord from September to June 2012, 30 and 70 km from Helheim Glacier (MM, UM respectively), show large velocity fluctuations on time scales of several days. Note, in particular, the large variability of temperature of the Atlantic water layer (lower panels). This high frequency variability is due to changes on the shelf – many of which are due to passing storms (Jackson et al. 2014).

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 2013 included on-going processing and analysis of data obtained thus far, reoccupying the hydrographic section on a cruise of R/V Endeavor, upgrading the project website, and continuing to write up results for journal publication. MIT/WHOI Joint Program student I. Le Bras, who is supported on this project, successfully passed her general exams and is beginning her dissertation research investigating the North Atlantic's deep western boundary current. Finalized mooring and cruise datasets available to date have been submitted to the OceanSites data archive.

Online data

http://www.whoi.edu/science/PO/linew/index.php

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

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The objective of this program is to use frequency-dependent analysis of processes important to AMOC dynamics in order to better understand inter-model differences that are relevant to understanding why the nature of AMOC variability is not consistent across models.

Recent results

The dynamics of the Atlantic Meridional Overturning Circulation (AMOC) vary considerably between different climate models; for example, some models show clear peaks in their power spectra at multi-decadal frequencies, while others do not, with various mechanisms having been proposed to explain these differences. In order to better understand these frequency-dependent differences between different GCMs, the study uses transfer functions to look at individual process representations in the frequency domain. Transfer functions provide an estimate of the linear, causal, frequency-dependent relationship between the input and output of any process. This technique was first applied to compare ENSO dynamics between models and between models and data; here it is applied first to understand differences between models in AMOC variability in pre-industrial control runs from CMIP5 (MacMartin et al. 2013), and are now looking at differences in AMOC variability for a single model between its pre-industrial and a high-CO_2 simulations (using 4xCO_2 to maximize signal to noise).

The project first estimated the frequency-domain relationship between different fields and the resulting AMOC response, using the output of CMIP5 and CMIP3 control runs for eight different models, with a specific focus on GFDL CM2.1 and CCSM4, which exhibit rather different spectral behavior. 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.

Next, two particular proposed mechanisms were explored for explaining inter-model differences in AMOC variability: differences in Labrador Sea stratification, and excitation by westward propagating subsurface Rossby waves. Increased Labrador Sea stratification reduces the penetration of surface forcing to depth; however, by resolving this process in the frequency domain, there is no evidence to suggest that differences in the stratification are responsible for the presence or absence of spectral peaks in AMOC variability. A Rossby wave mechanism has also been suggested for explaining spectral peaks in AMOC. The project finds that an east-west subsurface temperature gradient related to such propagating waves is not more effective at exciting AMOC variability than a comparable unrelated temperature anomaly, nor more effective at exciting AMOC in GFDL CM2.1 (which has a spectral peak in AMOC variability) than in CCSM4 (which does not). However, the power spectrum of this subsurface temperature gradient indicates that it is itself preferentially excited at a 20-year period in GFDL CM2.1 relative to CCSM4, indicating that this mechanism may indeed play a role. Both the differences observed in response to surface forcing and the evaluation of proposed mechanisms to explain variability are clarified by using a method that explicitly computes the frequency-dependence.

The same frequency-dependent process analysis tools have also been applied to enhance our understanding of ENSO process dynamics (Linz et al. 2014).

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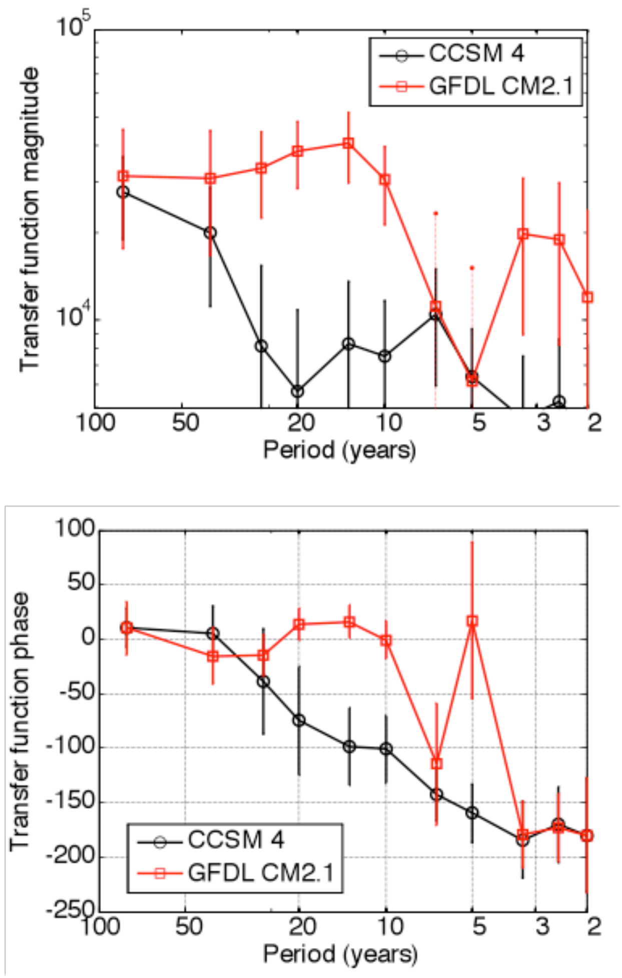

Figure 1. Transfer function from high latitude surface salinity to strength of AMOC circulation (amplitude of projection onto first eof of variability) for CCSM4 (black) and GFDL CM2.1 (red); magnitude of frequency-dependent relationship (left) and phase (right). The GFDL model has a pronounced peak in the spectrum of interannual AMOC variability at roughly 20 year period, while CCSM4 shows only broadband variability; these differences are evident in this and other transfer functions, illustrating that AMOC in the GFDL model is more sensitive to high-latitude sea surface perturbations in this frequency range than CCSM4, helping to explain the differences in variability between the models. The phase (at right) is a useful guide for causality; the phase lag here indicates that perturbations in surface salinity lead AMOC variability.

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

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This project has two major objectives. First, the project will test and examine a hypothesis: the Atlantic warm pool (AWP) plays a negative feedback role in the AMOC. Second, the project will investigate common patterns of global SST biases in CMIP5 climate models, which are commonly linked with the simulated AMOC.

Recent results

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

- A large (small) AWP is associated with a local freshwater gain (loss) to the ocean, less (more) moisture transport across Central America, and a local low (high) sea surface salinity.
- Observations and model experiments show that the AWP plays a negative feedback role that acts to restore the AMOC after it is weakened or shut down. On one hand, as the AMOC weakens, its northward heat transport reduces and thus the North Atlantic Ocean cools and the AWP becomes small. On the other hand, a small AWP decreases rainfall in the tropical North Atlantic and increases the cross-Central American moisture export to the eastern North Pacific. Both of these factors tend to increase salinity in the tropical North Atlantic. Advected northward by the ocean circulation, the positive salinity anomaly increases the upper-ocean density in the deep-water formation regions and thus strengthens the AMOC.
- Both observations and most of CMIP5 models show that the warm (cold) phase of the Atlantic Multidecadal Oscillation (AMO) is associated with a surface warming (cooling) and a subsurface cooling (warming) in the tropical North Atlantic Ocean. It is shown that the anticorrelated ocean temperature variation in the tropical North Atlantic is caused by the meridional current variation induced by the AMOC variability. Thus, the tropical North Atlantic temperature variation can be taken as a fingerprint for the AMOC.
- The project finds common patterns of global SST biases in 22 climate models, which are commonly linked with the AMOC. A simulated weak AMOC is associated with cold biases in the entire Northern Hemisphere with an atmospheric pattern that resembles the Northern Hemisphere annular mode. The AMOC weakening is also associated with a strengthening of Antarctic bottom water formation and warm SST biases in the Southern Ocean. It is also shown that cold biases in the tropical North Atlantic and West African/Indian monsoon regions during the warm season in the Northern Hemisphere have inter-hemispheric links with warm SST biases in the tropical southeastern Pacific and Atlantic, respectively. The results suggest that improving the simulation of regional processes may not suffice for overall better model performance, as the effects of remote biases may override them.

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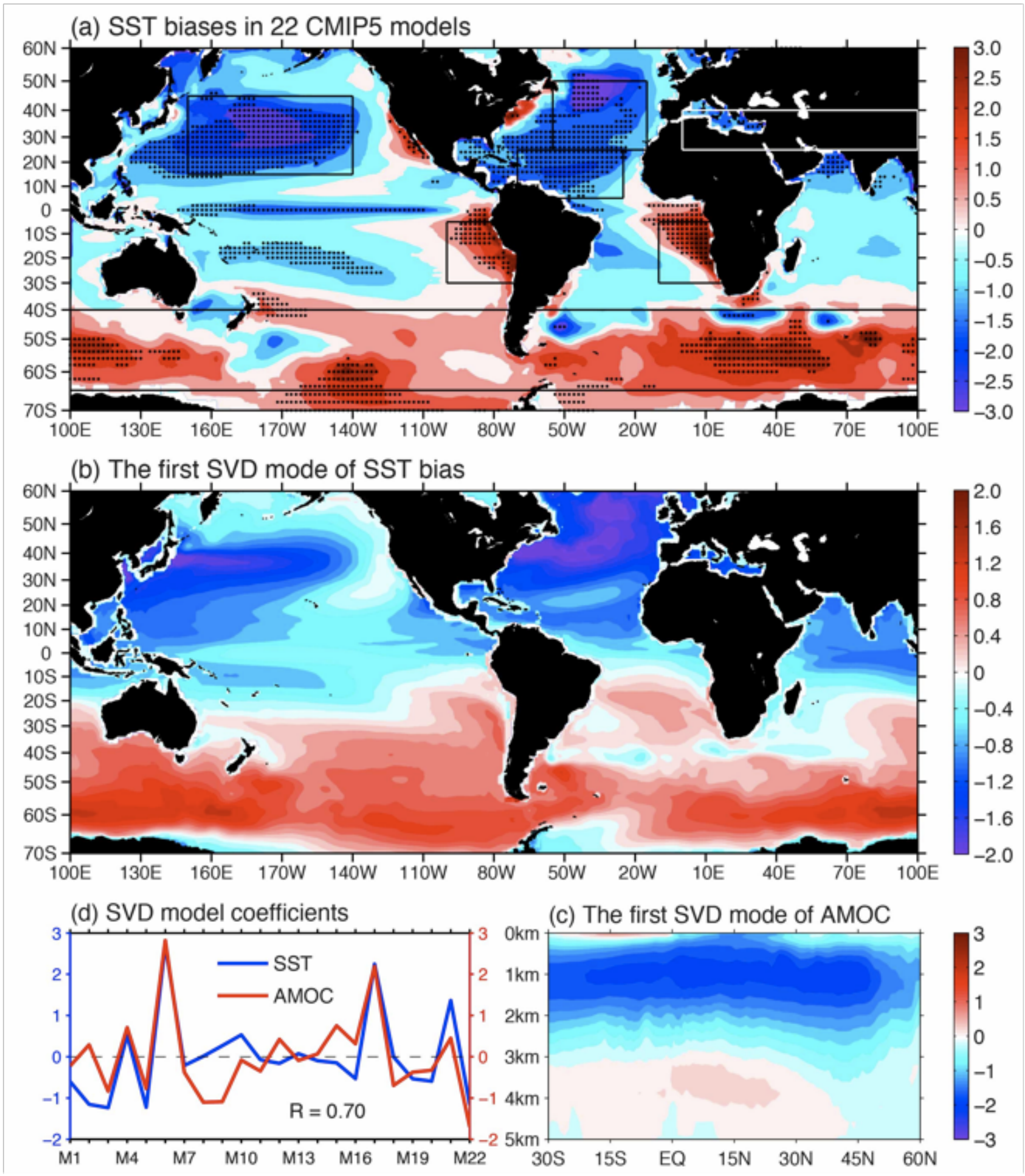

Figure 1. Global SST bias and its relationship with the AMOC. (a) The annual-mean SST (°C) bias averaged in 22 climate models. The SST bias is calculated by the SST difference between the model SST and ERSST. The dots denote where at least 18 of 22 models have the same sign in the SST bias. (b, c) Spatial maps of SST bias and the AMOC (Sv), and (d) coefficients for the first inter-model SVD mode. The x-axis in (d) represents different models. The coefficients have been normalized by their own standard deviations. The correlation R between the SST and AMOC coefficients is 0.70. Global SST biases, therefore, strengthen as the AMOC circulation weakens.

Agulhas Leakage and Its Impact on the Atlantic Meridional Overturning Circulation in the CCSM4

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This study analyzes the representation and impact of Agulhas Leakage in an IPCC-class climate model, the Community Climate System Model version 4 (CCSM4). The relatively low spatial resolution of this class of models (nominally 1°) does not allow for the explicit representation of the mesoscale processes that control Agulhas Leakage. Consequently, it was found that the volume exchange between the South Indian and Atlantic Oceans is overestimated by a factor of three in the CCSM4 compared to observations (Weijer et al. 2012). In view of several studies (e.g., Weijer et al. 2002; Biastoch et al. 2008), that suggest a control of Agulhas Leakage on the Atlantic Meridional Overturning Circulation (AMOC), it is important to assess the consequence of this bias.

The aim of this study was therefore to investigate whether Agulhas Leakage impacts the strength of the AMOC in the CCSM4. Using 500 yr of an 1850 pre-industrial control integration, the study first generated a time series of Agulhas Leakage salt import F_S, using a Lagrangian particle tracking method. A coherence analysis was then performed between F_S and the AMOC strength at different latitudes (Figure 1). Significant coherences were found only in a few period bands (50-100 yr; 25 yr; 3-5 yr). In addition, the associated phase differences were inconsistent with a causal impact of Agulhas Leakage variability on the AMOC. So this analysis does not support the hypothesis that Agulhas Leakage impacts the AMOC in a significant way.

However, a comparison between the model salinity and an observational climatology showed a considerable bias in the salinity field of the southwestern South Indian Ocean; in particular, the sharp salinity front of the Agulhas Retroflection turned out to be absent in the model. Consequently, salinity variability in the southeastern South Atlantic Ocean is underestimated by a factor of five.

The project concludes that: i) the overestimation of Agulhas Leakage in the CCSM4 leads to a homogenization of the southeastern South Atlantic and southwestern South Indian Ocean; ii) this homogenization results in a too weak salinity variability in the southeastern South Atlantic; iii) and hence the result that Agulhas Leakage does not influence the AMOC is inconclusive.

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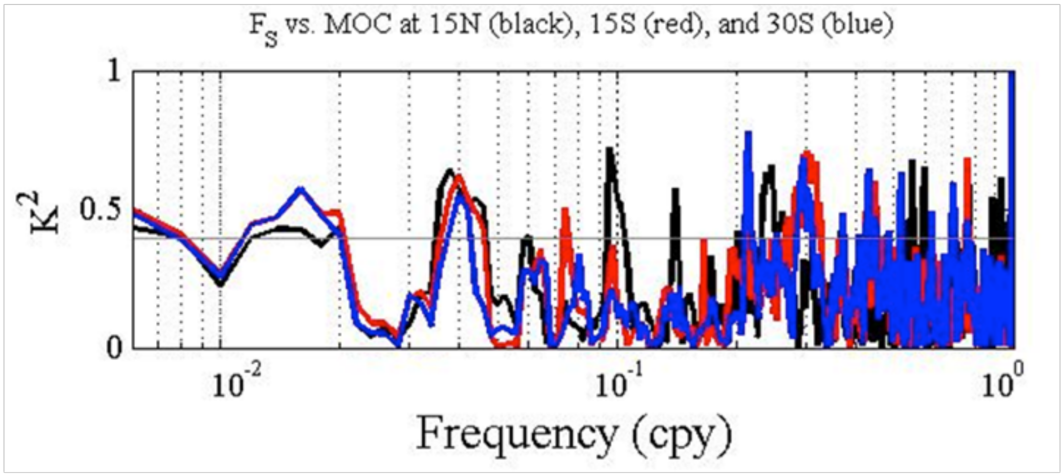

Figure 1. Coherence between the Agulhas Leakage salt flux (F_S) and the AMOC strength at select latitudes. Significant coherences are found only in the 50-100 year, 25 year, and 3-5 year period bands. However, the associated phase relationships are inconsistent with a causal impact of Agulhas Leakage on the AMOC.

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

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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 deep convection and subsurface thermal structure estimated from satellite multi-sensor data.

Recent results

- A dipole pattern measured by satellite altimetry was analyzed (Li et al., 2012a). The project 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).

- Since the sea surface changes in response to many forcings occurring at different time scales, analysis of the interactions between the different scales of variation is important to understand how sea level has varied in the past and how it will vary in the future. Geographically uneven sea level trends (SLT) in six selected areas in the North Atlantic were analyzed using the monthly mean altimetry sea surface height anomaly (SSHA) from January 1993 to December 2011. In order to understand the different time scales in SSHA variability, the data were decomposed into intra-annual, 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 at 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 down swinging 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 up swinging inflection dominated in the regions where sea level was significantly decreasing after about 2000, close to the North Atlantic current and Northern Recirculation gyre. This study helps to understand whether sea level changes in different regions are in phase or out of phase, and with how much lag (Jo et al., 2013).
- The sea level variations in the North Atlantic subpolar gyre are dominated by the annual cycle and the long-term increasing trend. In comparison, the SSHA along the Gulf Stream is dominated by variability at intra-seasonal and annual timescales. The sea level rise in the subpolar gyre 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 subpolar gyre. To identify contributing factors for these changes, the heat content balance (equivalent variations in the sea level) in the subpolar gyre 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 subpolar gyre might be related to the deep ocean convection process and the propagation of the AMOC variations between high- and mid-latitudes (Li et al. 2012b).
- The mechanisms for convected water to restratify in the Labrador Sea are still under debate. The Labrador Sea restratification after deep convection in the 2007 – 2008 winter is studied with an eddy-resolving numerical model. The modeled mixed layer depth during wintertime resembles the Argo observed mixed layer very well, and the lateral heat flux during the subsequent restratification is in line with observations. The Irminger Rings (IRs) are reproduced with fresher caps above the 300 m depths, and they are identified and tracked automatically. The model underestimates both the number of IRs into the convection area and the heat they carry. The underestimation is most likely caused by the errors in the direction of the West Greenland currents in the model, which causes more IRs propagating westward, and only the IRs originating south of 61.5°N are able to propagate southward, yet with speed much slower than observed speed. The model still observed three eddies propagating into the convection area during restratification phase in 2008, and their thermal contribution ranges from 1% to 4%. If more modeled IRs can propagate into the convection area, the IRs contribution would be far from marginal, or even dominantly significant. The more detailed and direct heat flux by IRs is difficult to derive due to strong fluctuation of the identified eddy radius. Nevertheless, the modeled lateral heat flux is largely comprised by that of the boundary current eddies and convective eddies, thus it is possible for the model to maintain an acceptable thermal balance (Zhang and Yan, 2013).

- The dominant modes of variability in the temperature and ocean heat content of the central Labrador Sea were investigated using the Hilbert-Huang Transform (HHT) based on collected Argo profiles. Warming trends of approximately 0.03°C yr^{-1} were observed in the entire water column. A strong annual cycle exists and dominates at the 500 m depth, while signals at the interannual timescales can explain most of the variability at the 1000 m and 1500m depths. Further analysis on the timescales of interannual variability indicates longer periods of signals at deeper layers. These interannual signals are closely correlated to the variability of deep convection in the Labrador Sea, which has a typical mixed layer depth (MLD) of 1000 m with an intermittent enhancement of MLD > 1500 m. The Hilbert spectrum from heat content (0 – 1000 m) in the Labrador Sea interior reveals two important components at frequencies of 0.8 ~ 1.2 cycle yr-1 and 0.2 ~ 0.3 cycle yr^{-1}, respectively, superimposed on the overall warming trends. The former corresponds to the dominant seasonal cycle due to surface heating, while the latter is concomitant with the timing of the reoccurrence of strong convection events. The cumulative North Atlantic Oscillation (NAO) index is significantly correlated to the low frequency variations in the heat content reconstructed from the EEMD results. Therefore, the interannual signals in the Labrador Sea at especially the intermediate layers are attributed to the deep convective processes influenced by both oceanic and atmospheric conditions. Moreover, over longer timescales, underlying warming trends from a nine year record might be part of multi-decadal variations that reflect the Atlantic Multi-decadal Variability (Li et al., 2013).

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Atmospheric Forcing of Marginal-Sea Overflows

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Effective Capacity of the Nordic Seas Dense Water Reservoir

The overflow of the dense water mass across the Greenland-Scotland Ridge (GSR) from the Nordic Seas drives the Atlantic Meridional Overturning Circulation (AMOC). The Nordic Seas is a large basin with an enormous reservoir capacity. The volume of the dense water above the GSR sill depth in the Nordic Seas, according to previous estimates, is sufficient to supply decades of overflow transport. This large capacity buffers overflow's responses to atmospheric variations and prevents an abrupt shutdown of the AMOC. In this study, a numerical and an analytical model are used to show that the effective reservoir capacity of the Nordic Seas is actually much smaller than what was estimated previously. Basin-scale oceanic circulation is nearly geostrophic and its streamlines are basically the same as the isobaths. The vast majority of the dense water is stored inside closed geostrophic contours in the deep basin and thus is not freely available to the overflow. The positive wind-stress curl in the Nordic Seas forces a convergence of the dense water toward the deep basin and makes the interior water even more removed from the overflow-feeding boundary current. Eddies generated by the baroclinic instability help transport the interior water mass to the boundary current. But in absence of a robust renewal of deep water, the boundary current weakens rapidly and the eddy-generating mechanism becomes less effective. The study indicates that the Nordic Seas has a relatively small capacity as a dense water reservoir and thus the overflow transport is sensitive to climate changes. The results have been published in Journal of Physical Oceanography in 2013.

Mechanisms of the Denmark Strait Overflow Pathways

The East Greenland Current (EGC) had long been considered the main pathway for the Denmark Strait Overflow (DSO), a major source of the NADW that drives the lower limb of the AMOC. Recent observations, however, indicate that the North Icelandic Jet (NIJ), which flows westward along the north coast of Iceland toward the Denmark Strait, is a major separate pathway for the DSO, one that accounts for roughly half of the DSO transport. The dynamics that govern the DSO pathways and their alternations are investigated by using numerical and theoretical models. In the simulations, a westward and NIJ-like boundary current emerges along the northern Icelandic coast as a robust feature and a main pathway for the Denmark Strait Overflow. Its existence can be explained through consideration of circulation integrals applied along advantageous contours. Some effects of wind stress forcing are also examined. The overall positive curl of the wind forces cyclonic gyres in both layers, enhancing the EGC, and weakens but does not eliminate the NIJ. It also modifies the sign of deep circulation in various sub-basins and alters the path by which overflow water is brought to the Faroe Bank Channel, all in ways that bring the idealized model more in line with observations. The sequence of numerical experiments thus separates the effects of wind and buoyancy forcing and shows how each is important. The result has been submitted to Journal of Physical Oceanography.

Wind-driven AMOC Variability at the AMOC-MOCHA line

The oceanic adjustment to wind-stress forcing involves propagation of Rossby, topographic and boundary waves. So remote forcing from different latitudes would probably influence the AMOC transport at 26.5˚N. The project uses a two-layer and wind-driven ocean model with realistic topography and wind stress forcing to investigate both local and remote forcing mechanisms. The results show that the wind-stress curl at the eastern boundary does not dominate the annual variability of the mid-ocean geostrophic transport. The AMOC transport remains robust when a wall is inserted at 30°W to block forcing from region to the east of this wall. Furthermore, remote forcing from the subbpolar basin is found to have a considerable impact on the AMOC transport at 26.5°N. A manuscript is submitted for publication in 2014.

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

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The objective of this project is to study how the Atlantic Meridional Overturning Circulation (AMOC) modifies sea level rise along the East Coast of the US and how sea level rise patterns along this coast and in the North Atlantic can be used as an important fingerprint to detect AMOC variability and change. The IPCC Fifth Assessment Report has listed sea level rise among the top in vulnerability and impact assessment. Regional sea level rise variability is also one of the Grand Challenges identified by the World Climate Research Programme as a high priority. Numerous tide gauges provide long-term observation of coastal sea levels while satellites have accurately monitored the global dynamic sea level (i.e., sea surface height relative to the geoid) since 1993. The dynamic sea level reflects vertically integrated ocean properties such as temperature, salinity, density, and water mass distribution. Hence, there is inherent linkage between the AMOC and dynamic sea level. In the North Atlantic, the AMOC is an important factor in causing regional sea level rise deviation from the global mean. As a new project supported by NOAA CPO and started in September 2013, it plans to address important AMOC sea level rise issues and have made the following progress. Such knowledge can be applied to altimetric data assimilation in a coupled climate model to improve AMOC reanalysis and prediction.

Recent results

- With long-term tide gauge data, the project has identified two sea level rise patterns along the East Coast of the US: a middle-high pattern (faster sea level rise in the mid-Atlantic region and slower sea level rise to the north and south) during much of the 20th century; and a north-high south-low pattern (faster/slower sea level rise north/south of Cape Hatteras) during the past two decades (Figure 1). In addition to land vertical movement, these two coastal sea level rise patterns reflect two modes of dynamic sea level rise variability and change in the North Atlantic as simulated by the GFDL ESM2M global earth system model. We have investigated the mechanisms for the two modes and how they are linked to the AMOC variability and change.

- With the ESM2M, the project has studied the influence of a slowdown/shutdown of the AMOC in the idealized water-hosing experiments on the South America monsoon precipitation and the carbon cycle in the Amazon rainforest region.
- The project has led and contributed to the international CORE-II (Coordinated Ocean-ice Reference Experiments) sea level simulations and analysis.

Significant findings include

- The observed faster sea level rise in the mid-Atlantic region during the 20th century (Figure 1) is related to the overall northward and onshore shift of the Gulf Stream. The observed faster sea level rise north of Cape Hatteras during the past 20 years (Figure 1) is mainly induced by the decline of ocean density contrast across the Gulf Stream downstream of Cape Hatteras, that is, the baroclinic process associated with the AMOC variability and change (Yin and Goddard 2013). The two dynamic sea level modes are generally captured by ESM2M in the 20th century simulation and 21st century projection (Figure 1).
- In the water-hosing experiments, a significant weakening of the AMOC can alter seasonality and total amount of the South America monsoon precipitation, leading to net changes in the carbon uptake of the Amazon rainforest, thereby providing feedbacks to climate change (Parsons et al.2014).
- Provided the observational estimate of the ocean surface forcing, most of the CORE-II models can generally capture the sea level rise pattern such as in the Pacific during the past two decades. However, a realistic simulation of the global mean steric sea level rise is a challenge (Griffies et al. 2014).

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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.

Recent results

Identifying the prime drivers of the twentieth-century multidecadal variability in the Atlantic Ocean is crucial for predicting how the Atlantic will evolve in the coming decades and the resulting broad impacts on weather and precipitation patterns around the globe. Recently, Booth et al. showed that the Hadley Centre Global Environmental Model, version 2, Earth system configuration (HadGEM2-ES) closely reproduces the observed multidecadal variations of area-averaged North Atlantic sea surface temperature in the twentieth century. Aerosol indirect effects that modify net surface shortwave radiation primarily drive the multidecadal variations simulated in HadGEM2-ES. On the basis of these results, Booth et al. concluded that aerosols are a prime driver of twentieth-century North Atlantic climate variability. However, here it is shown that there are major discrepancies between the HadGEM2-ES simulations and observations in the North Atlantic upper-ocean heat content, in the spatial pattern of multidecadal SST changes within and outside the North Atlantic, and in the subpolar North Atlantic sea surface salinity. These discrepancies may be strongly influenced by, and indeed in large part caused by, aerosol effects. It is also shown that the aerosol effects simulated in HadGEM2-ES cannot account for the observed anticorrelation between detrended multidecadal surface and subsurface temperature variations in the tropical North Atlantic. These discrepancies cast considerable doubt on the claim that aerosol forcing drives the bulk of this multidecadal variability.

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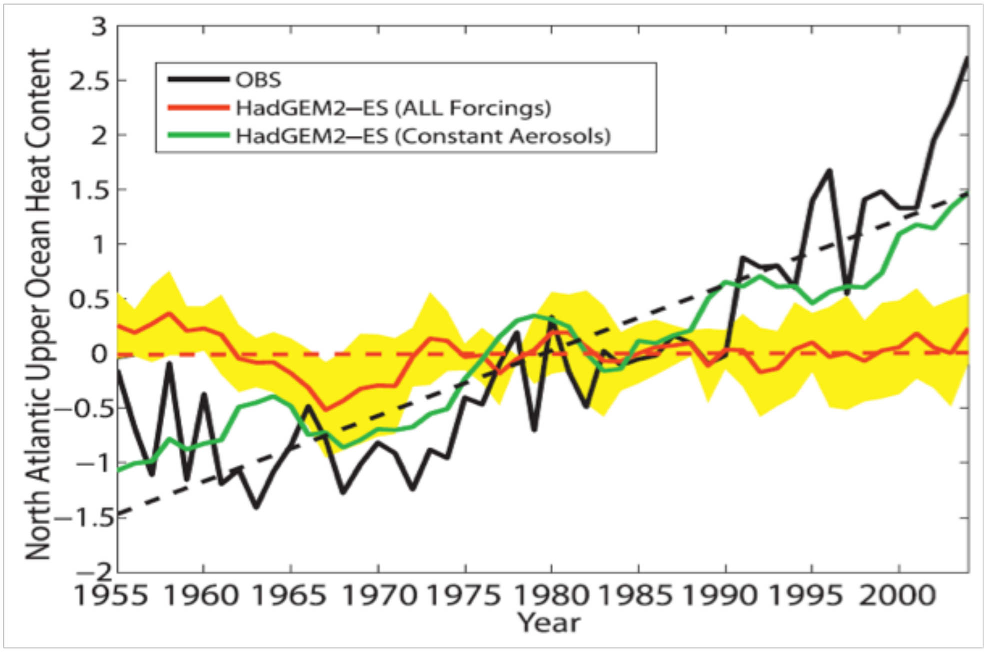

Figure 1. North Atlantic upper-ocean heat content anomaly. Red line: area-averaged North Atlantic upper-ocean heat content anomaly (x10^{22} J) (0–700 m; 0–60°N, 75–7.5°W) from ensemble mean of HadGEM2-ES all-forcings simulations. Yellow shading: 1 std dev of ensemble spread of all forcings. Green line: ensemble mean from constant-aerosols historical simulations. Black line: observations. All anomalies are relative to 1955–2004 mean. The dashed lines are linear trends for the respective variables. The 1955–2004 trend is 0.599 x 10^{22} J /decade for observations and 0.003 x 10^{22} J /decade for HadGEM2-ES all-forcings ensemble mean.

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