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

The U.S. AMOC Science Team

Executive Summary

The Joint Subcommittee on Ocean Science and Technology (JSOST) identified the improved understanding of the mechanisms behind fluctuations of the Atlantic Meridional Overturning Circulation (AMOC) as a near-term priority in the Ocean Research Priorities Plan issued in January of 2007. In response to this near-term priority, a panel of scientists developed a five-year implementation strategy, released in October of 2007, which laid the groundwork for an inter-agency program that will develop 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 and NOAA). The report herein is the third annual progress report submitted by the U.S. AMOC Science Team. The purpose of this report is to summarize progress on the main objectives of the program, identify any programmatic gaps, and make recommendations on near-term research priorities for the program.

Planning activities within the U.S. AMOC Program are organized under four “task teams” consisting of groups of program PI’s, which were slightly realigned after the 2010 Annual Meeting held on 7-9 June in Miami. The revised task teams and their leadership for the coming year are:

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

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

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

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

The task team leaders, together with the Science Team chair, form the AMOC Program Executive Committee and provide overall program guidance and liaison with the U.S.

CLIVAR Office and agency program managers.

Progress on the three main AMOC program objectives during 2010 can be summarized as follows:

1. The design and implementation of an AMOC monitoring system

AMOC monitoring in the U.S. is presently accomplished by a collection of field programs, several of which were already underway at the creation of the program. Several nationally and internationally-funded global-scale programs are presently returning data that contribute to AMOC monitoring, include Argo, JASON, the Global Drifter Array and the collection of satellites returning ocean surface and meteorological information. Some recent research highlights from these programs include:

- Beginning in 2002, AMOC strength estimates at 41°N have been derived using a combination of satellite altimetry and in-situ (ARGO) data, yielding a mean of 15.5 ± 2.4 Sv for the AMOC transport and 0.52 ± 0.18 PW for the associated heat transport.
- The first four years of observations available from the RAPID-MOCHA program at 26.5°N show that the mean MOC estimate remains stable at 18.7 Sv with statistical uncertainty of 2.1 Sv, and the associated meridional ocean heat transport (MHT) is 1.33 +- 0.14 PW. The MHT is highly correlated with the MOC strength, and both the MOC and the MHT show a significant annual cycle associated primarily with changes in the interior ocean circulation driven by annual wind stress curl variability.
- Results from the Florida Straits measurement program and historical data analysis show that from 1964 to the present there is no indication of a statistically significant trend in Florida Current transport, and interannual and longer time scale variations represent 10% or less of the total variance.
- The Line-W program at 39°N has estimated the time-averaged top-to-bottom meridional transport of the waters shoreward of the Gulf Stream to be -36.2 ± 3.4 Sv, with a notable shift in intermediate water potential vorticity that appears consistent with the time history of deep convection in the Labrador Sea.
- The 9.5 year long time series now available from the MOVE line 16°N indicates an approximately 20% decrease in the southward North Atlantic Deep Water (NADW) since 1999, significant at an 85% confidence level.
- Analysis of historical observations in the South Atlantic off the coast of Brazil shows a multidecadal North Brazil Current transport variability that lags by a few years Labrador Sea deep convection, and is coherent with basin-scale SST fluctuations linked to the Atlantic Multidecadal Oscillation (AMO).
- Analysis of recent RAFOS float observations and model simulations show a dominant interior pathway for the spreading of Labrador Sea Water (LSW),

rather than a direct pathway along the western boundary.

- A very successful glider study of the dense overflows at the southern flank of the Iceland Faroe Ridge was completed, revealing the dilution of the dense Iceland-Scotland Overflow Water as it moves round the Iceland Basin to join the North Atlantic Deep Water branch of the AMOC.
- New satellite techniques and analysis have been developed to investigate deep convection activity in the Labrador Sea, and the contribution of Greenland ice sheet melting to sea level rise.
- Significant progress has been made in developing observing system simulation experiments (OSSEs) and adjoint-model sensitivity experiments to study the impact of various satellite and in-situ observations on estimates AMOC strength and variability, and to assess latitudes where cross-basin AMOC monitoring may be particularly effective.
- Major planning activities took place in 2010 toward the implementation of internationally coordinated trans-basin AMOC observing systems in both the subtropical South Atlantic (SAMOC) and subpolar North Atlantic (OSNAP).

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

Past studies have indicated that decadal-to-multidecadal Atlantic SST fluctuations contribute significantly to global climate variability. The extent to which these SST fluctuations are associated with or driven by AMOC variability on similar time scales remains debatable and is difficult to establish through observations. However, judged by coupled model consensus, there is an increasingly robust link between AMOC variability and SSTs in the subpolar Atlantic. Other impacts associated with decadal-to-multidecadal Atlantic SST fluctuations are the changes in Atlantic tropical storm activity, large fluctuations in the sub-Saharan Sahel region rainfall associated with swings in the Atlantic ITCZ, U.S. hydroclimate, and far reaching association with decadal variability of the Asian Monsoon intensity. Such connections and others continued to be the focus of AMOC-related studies in 2010, as part of this program and others. Notable achievements by PIs involved in the US AMOC program include the following:

- Model-based assessment of the impact of AMOC variability on Arctic surface air temperature and sea ice cover shows an association between the positive phase of AMOC and the recent decline in Arctic sea ice cover in the Labrador, Greenland, and Barents Seas. This indicates that AMOC variability can enhance or diminish the impact of anthropogenic greenhouse warming and its effect on the Arctic.
- The impact of North Atlantic multidecadal SST variability (AMV) on variability of precipitation and surface temperature over the globe, studied in both observations and in the multi-model ensemble of IPCC AR4 CGCMs, shows a large degree of consistency in the prominent regional features. A multi-model depiction of AMV impacts in pre-industrial, 20th and 21st century integrations

further indicates that the impacts remain steady with the changing climate.

- Further work on the atmospheric mechanisms linking the AMV to North and South American hydroclimate variability confirms the tropical Atlantic region as the key region for creating the remote AMV impacts, where the warm phase of the AMV leads to droughts both in the US West and northern Mexico and in southeastern South America.
- Model study of the tropical Atlantic SST response to AMOC variability suggest that the SST and associated precipitation response is highly nonlinear, with the tropics warming only if the AMOC change is below a threshold value, indicating that complex and competing atmosphere-ocean processes may be involved in the rainfall response to AMOC variability.

3. An assessment of AMOC variability mechanisms and AMOC predictability

Assessments of the physical mechanisms underlying AMOC variability, and potential predictability of the AMOC, are currently under intense study. Approaches including initial condition constraints and transient boundary forcing to investigate both natural and anthropogenically-induced variations are being pursued, as are investigations of natural internal variability. NCAR and GFDL, as well as international modeling centers, are currently using model output from the IPCC AR5/CMIP5 to attempt to identify robust AMOC variability mechanisms. Some important findings from these and other efforts include:

- A 1948-2007 NCAR ocean-ice hindcast forced with atmospheric state fields exhibits a large upward trend in AMOC strength between 1960 and 2000 along with an associated AMV-like surface temperature signature that compares well with observations.
- A statistical predictive model of AMOC variability based on subsurface temperature and sea surface height fingerprints of the AMOC has been developed from observations and output from the GFDL CM2.1 control simulation, which predicts a weakening of AMOC strength in a few years after its peak around 2005.
- Analysis of altimetric and drifter observations suggests that the warming and salinity increase in the northern Atlantic during the past decade is through the opening of exchange pathways between subtropical and subpolar regions, leading to enhanced flow from the Gulf Stream directed toward higher latitudes.
- Analysis of CCSM3 model results shows two regimes of AMOC variability, one with a very regular and strong decadal variability and one with irregular and weak multi-decadal variability. The weak multi-decadal AMOC variability appears to be an ocean-only mode associated with the advection of density anomalies driven by stochastic atmosphere around the subpolar gyre, in contrast to the previously documented strongly decadal regime which has a significant multi-decadal spectral peak in the atmospheric forcing represented by the North

Atlantic Oscillation.

- AMOC variations in the GFDL CM2.1 coupled climate model evaluated in both depth and density space show significantly greater meridional coherence in density space, with a several-year time lead between subpolar and subtropical latitudes, potentially providing a more useful predictability of basin-wide AMOC variability.
- Model studies of the processes connecting the AMOC to the Antarctic Circumpolar Current (ACC) suggest that the ACC stratification exerts a fundamental control over the AMOC strength, while Ekman transport and eddy-driven heat/salt fluxes at the ACC-Atlantic boundary are of secondary importance.
- Model-dependencies in AMOC variability are becoming increasingly clear. The new version of the Community Climate System Model (CCSM4) shows much less overall AMOC variance than found in CCSM3, with only weak spectral peaks exceeding red noise at timescales longer than 50 years. Preliminary analysis of these simulations as well as of the MIT coupled model suggests that the pacemaker appears to be set in the subpolar basin of the Atlantic, with AMOC variability in the subtropics lagging that of buoyancy anomalies in the subpolar gyre.

These research highlights show that our knowledge of AMOC variability and its linkages to climate variability is advancing on numerous fronts, but that a full picture of AMOC variability, its current trends throughout the basin, and the mechanisms controlling its variability, is not yet in hand. Overall funding for the program has fallen short of the expectations set when the program was initiated in the spring of 2007. In order to achieve the program goals, it is important that funding levels quickly be brought to those originally intended for the program.

Based on discussions at the 2010 Annual Meeting, several high priority, near-term research objectives for the program were identified:

1. Assessing the meridional coherence of AMOC changes should be a continued focus of prognostic models, state estimation models, and enhancement of the AMOC observing system. The design of monitoring systems for the time varying strength of the AMOC in the subpolar North Atlantic and subtropical South Atlantic should be completed this year and implemented during 2012. The importance of deep temperature and salinity measurements (i.e. deep ARGO) in monitoring AMOC variability should also be assessed.

2. Assimilation modeling efforts should focus on reaching a consensus on the variability of the AMOC over the past few decades, and on placing realistic uncertainty bounds on these estimates. It is important that we understand the uncertainties of existing

estimates and the accuracies required to detect climatically important AMOC-related changes.

3. Studies aiming to develop fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations should be further encouraged and supported. Particular focus should be on understanding the linkage between AMOC variability and SST variability, both from a diagnostic and mechanistic viewpoint.

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

5. Further effort needs to be directed toward understanding AMOC variability mechanisms and the model dependencies of these variability mechanisms. To address this issue, a detailed comparison study for the AMOC mechanisms should be coordinated among modeling groups. A focused effort is also needed to develop a synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational data.

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

7. In coordination with the near-term prediction experiments being conducted by modeling centers for the IPCC AR5, an inter-comparison study should be performed to investigate the robustness of AMOC predictions among simulations using various models. These efforts should seek collaboration with the U.S. CLIVAR Decadal Predictability Working Group as well as the International CLIVAR Working Group on Ocean Model Development and Global Synthesis and Observational Panel.

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

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Implications for Rapid Climate Change

A. INTRODUCTION

In January 2007, the Joint Subcommittee on Ocean Science and Technology (JSOST) 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[1], released in October of 2007. The five-year implementation plan laid the groundwork for an inter-agency program that will 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[1] in March of 2008. This Science Team, comprised of all funded investigators under this program, bears the responsibility of accomplishing the program objectives with guidance and oversight from the supporting agencies. As part of this responsibility, the Science Team produces annual progress reports that are intended to 1) facilitate the dissemination of recent research results, 2) help the agencies as well as the scientific community identify gaps in our understanding and measurement of the AMOC, and 3) aid the coordination of efforts across agencies. A further goal of the progress reports is to provide concise and timely communication to international collaborators on the US AMOC efforts, including the identification of evolving science and monitoring issues.

The report herein is the third annual progress report submitted by the US AMOC Science Team. This report focuses on the progress of the three main program objectives, followed by an identification of high priority, near-term research objectives for the program.

B. PROGRESS ON PROGRAM OBJECTIVES

1. *The design and implementation of an AMOC monitoring system*

1.1 Results from existing observational programs

At present, the *in-situ* observational component of the U.S. AMOC program is comprised of a collection of field programs, a number of which were initiated prior to the kickoff of the U.S. AMOC program. The progress of each of these is summarized below, grouped by geographic domain. Further details may be found in the individual PI progress reports (Appendix 3).

1.1.1 Subtropical North Atlantic

The joint U.K.-U.S. program along 26°N is designed from the ground up to be full depth and full basin spanning. Two U.S. activities are directly associated with this program: a Florida Straits measurement effort and a western-Atlantic contribution to RAPID. Recent results from the Florida Straits measurement effort (Western Boundary Time Series, led by Baringer, Meinen and Garzoli) show that from 1964 to the present there is no indication of a statistically significant trend in Florida Current transport, and interannual and longer time scale variations represent 10% or less of the total variance. Additionally, work from this project has demonstrated that the variability of the MOC at 27°N has a large seasonal cycle, but no pronounced trend. Finally, the Florida Current, which also shows no strong trend, was shown to have a unique influence on east coast sea-level during several high water events.

Recent results from the western-Atlantic contribution to RAPID (An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic, led by Johns, Baringer, Beal and Meinen) using the first four years of observations show that the mean MOC estimate remains stable at 18.7 Sv with an rms variability of 4.9 Sv and the associated meridional ocean heat transport is 1.33 +- 0.39 PW, with a statistical mean uncertainty of 0.14 PW. Importantly, the meridional heat transport is highly correlated with the MOC strength, and the MOC carries 88% of the total heat transport. Additionally, these PIs have shown that the MOC and MHT have significant annual cycles primarily driven by annual wind stress curl variability near the eastern boundary.

Other sustained measurements in the subtropical North Atlantic include moored and shipboard measurements along an altimeter-satellite ground track running southeast of New England towards Bermuda. This program (Line W: A sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39°N led by Toole, Curry, Joyce, McCartney and Smethie) is focused on documenting interannual transport changes in the DWBC and Gulf Stream. Using the first 4 years of observations, the PIs have estimated the time-averaged top-to-bottom meridional transport of the waters shoreward of the Gulf Stream to be -36.2 ± 3.4 Sv and they have discovered a notable shift in intermediate water PV that appears consistent with the time history of deep convection in the Labrador Sea.

High-horizontal resolution upper-ocean velocity has been sampled since late 1992 by an acoustic Doppler current profiler (ADCP) mounted in the hull of the container vessel CMV Oleander that operates on a weekly schedule between New Jersey and Bermuda. Recent results from this program (The Oleander Project: Sustained observations of ocean currents in the NW Atlantic between New York and Bermuda, led by Donohue, Flagg and Rossby) show a correlation between the North Atlantic Oscillation (NAO) and both the Gulf Stream and the Sargasso Sea, suggesting that most of the observed variability in the Gulf Stream can be accounted for in terms of time-varying winds over the North Atlantic.

Shifting focus to the south, the MOVE program (Meridional Overturning Variability Experiment, led by Send and Lankhorst) along 16°N has returned a nearly ten year long deep transport record between Guadalupe and the Mid-Atlantic Ridge in order to monitor the strength of the lower branch of the Atlantic meridional overturning circulation. Recent analysis of the fully processed 9.5 year time series has shown a transport decrease in the southward North Atlantic Deep Water (NADW) by approximately 20% over this time period. This trend-fit is presently about 85% significant and consistent in amplitude, vertical structure and timescale with prior results.

A new observational program, focused on the abyssal waters of the subtropical North Atlantic, was funded this past year. This goal of this program (Dynamics of Abyssal Mixing and Interior Transports Experiment or DynAMITE, led by Curry and Polzin) is to assess the strength of, and linkages between, the horizontal and vertical components of the AMOC that flow through the interior basin between 20-40°N. A 6-element moored array was installed down the southeast flank of the Bermuda Rise in September 2010 and will remain in the water for a 1.5 year deployment period. In spring 2011, a microstructure/CTD/bathymetry survey will be conducted between 20°N, the Mid Atlantic Ridge and Bermuda Rise.

1.1.2 High Latitudes of the North Atlantic

While there is currently no *in situ* observational effort to measure the basin-spanning mass and heat transports in the subpolar North Atlantic, there are several programs focused on understanding mechanisms and transports believed to be linked to the overturning in this basin.

A study focused on the connectivity between the subpolar and subtropical gyres in the North Atlantic (Export Pathways from the Subpolar North Atlantic: Phase Two, led by Lozier and Bower) has analyzed recent RAFOS float observations as well as model simulations to show the dominance of interior pathways for the spreading of Labrador Sea Water (LSW). Recent work has shown that RAFOS floats released across the width of DWBC at 50°N are not biased by release position to follow interior pathways and that the detachment of LSW from the slope of the Grand Banks is a 2-d process, well captured by isobaric RAFOF floats. Finally, mesoscale variability of the Gulf Stream around the Grand Banks has a strong impact on LSW spreading pathways.

A study of the dense overflows at the southern flank of the Iceland Faroe Ridge with autonomous gliders (Analysis of eddies, mixing, and dense overflows at the Iceland-Faroe Ridge in the Northern Atlantic Ocean observed with Seagliders, led by Rhines and Eriksen) has revealed the dilution of the dense Iceland-Scotland Overflow Water as it moves round the Iceland Basin, through the Charlie-Gibbs Fracture Zone, eventually joining the North Atlantic Deep Water branch of the AMOC. Current work is focused on the vertical velocity field returned from deep Seaglider profiles, which in the path of the dense overflow waters, is being interpreted as a measure of turbulent mixing.

In an effort to understand and quantify freshwater inputs to the high-latitude North Atlantic, moored data from the Hudson Strait during 2005-2007 and 2008-2009 is being analyzed. This project (From Rivers to the Ocean: The Dynamics of Freshwater Export from Hudson Strait, led by Straneo and Lentz) aims to quantify the variability in the freshwater outflow from Hudson Strait and to understand which processes regulate its variability. Results to date show that the export of freshwater is highly variable and not correlated on interannual timescales with the river discharge into the bay. This discrepancy is attributed to the storage and release of freshwater from Hudson Bay as a result of variable wind forcing.

To investigate coupling between the ocean and the cyrosphere, repeated ship and helicopter-based synoptic surveys of a major glacial fjord in southeast Greenland fjord have been conducted. Recent measurements with this program (Glacier-Ocean Coupling in a Large East Greenland Fjord, led by Straneo, Hamilton, Sutherland and Stearns) show that sub-surface subtropical waters are present year round within the fjord and are rapidly replenished via wind-modulated exchanges with the shelf. Measurements also show that the Arctic and Atlantic Water layering has a pronounced impact on the vertical distribution of submarine melting and, therefore, exerts an important constraint on glacier stability. These results indicated that changes in the upper warm branch of the MOC will be rapidly and directly communicated to the Greenland Ice Sheet margins where, in turn, they have the potential to affect glacier stability.

1.1.3 Subtropical South Atlantic

A pilot program designed to measure the western boundary warm-upper limb and cold-deep limb components of the MOC at 34.5°S in the Atlantic is currently operational. This program (South Atlantic MOC project: SAM, led by Meinen, Garzoli, Baringer and Goni) began in 2009 and it is designed to be a first building block, coupled with a parallel French and South African effort on the eastern boundary, towards a future international trans-basin MOC observing array in the South Atlantic. The SAM program is in its early stages: initial results suggest a high degree of deep transport variability on scales of weeks to months, although better evaluations of the variability time scales will be available when the records are longer.

Another program uses South Atlantic historical observations near the western boundary off the coast of Brazil to identify variables and processes can be associated with decadal-to-multidecadal changes of AMOC. Recent work with this project (Decadal and Multidecadal Variability of the AMOC in Observational Records and Numerical Models, led by McPhaden' Zhang and Cheng) has revealed a multidecadal North Brazil Current (NBC)) variability that lags by a few years Labrador Sea deep convection. The NBC transport time series is coherent with the Atlantic Multidecadal Oscillation (AMO) in sea surface temperature that also has been widely linked to AMOC fluctuations. These results suggest that the observed multidecadal NBC transport variability is a useful indicator for AMOC variations.

1.2 Results from satellite-based measures of AMOC

Satellite observations have been providing crucial information on the time-evolving ocean circulation for many years, and will constitute a backbone of any comprehensive monitoring system of the AMOC. Among the most important we list here the series of satellite altimeters (TOPEX/POSEIDON, Jason, ERS, ENVISAT) available since 1992, time-varying gravity from GRACE since 2003, scatterometry from QuikSCAT since 1999, and sea surface temperatures from passive microwave radiometry since 1978. Only the Argo float network, which neared completion in 2007, matches the satellite's basin-to-global scale continuous coverage, a feature ultimately required for understanding oceanic shifts on climate time scales. Several projects have used satellite data, either in isolation or in combination with other data, to investigate aspects of the AMOC. Many of the results are reflected in various Community Whitepapers or Plenary Papers contributed to the OceanObs'09 symposium in Venice in the fall of 2009 (see http://www.oceanobs09.net/).

A preliminary assessment of time-varying ocean bottom pressure measurements from GRACE (Satellite Monitoring of the Present-Day Evolution of the Atlantic Meridional Overturning circulation, led by Shum and Kuo) points to remaining leakage problems and large uncertainties in GIA modeling. A method was developed to improve the mitigation of the Greenland ice melt signal contamination of the ocean, including the Labrador and Greenland Seas. A combination of altimetry, gravity and tide gauge data enabled an assessment of the sea-level rise budget and its contributions from Greenland ice-sheet fresh water freshening and steric sea-level.

A multi-sensor approach was also used in a study assessing the potential of monitoring North Atlantic deep ocean convection (DOC) through surface signatures (Satellite Multi-Sensor Studies of Deep Ocean Convection in North Atlantic Ocean, led by Yan and Jo). Analyses were conducted to identify cases of strong and week DOC in terms of their surface and sub-surface manifestation. Preliminary results indicate an ongoing decreasing strength of DOC since the mid-1990s in the Labrador Sea, despite several strong convection events. Statistical regression methods were developed to connect satellite date to available hydrographic profiles. Preliminary results are suggestive of a significant warming trend below the sea surface in the North Atlantic Ocean as well as in the Labrador Sea.

Diagnosing deep-water formation from satellite data was also one of the foci of the project "A NOPP Partnership for Atlantic Meridional Overturning Circulation (AMOC): Focused Analysis of Satellite Data Sets" (led by Minnett and Gentemann). Their results indicate that a direct link between the length and severity of winters and enhanced deep convection is difficult to make, and that SST time series by themselves are inadequate predictors of deep-water formation.

The value of global observing systems in supplementing mooring and ship-based data to estimate meridional volume and heat transports was evidenced by the "Monitoring the Atlantic Meridional Overturning Circulation using a combination of SST, altimeter, and Argo data" project (led by Willis). Corresponding AMOC estimates were made at 41°N, using a combination of satellite and in-situ data and merged with output from an ocean state estimate, yielding a 2004-2006 mean of 15.5 ± 2.4 Sv for the volume transport and 0.52 ± 0.18 PW for the heat transport.

1.3 Results from data assimilation / state estimation systems

Data assimilation or state estimation systems attempt to synthesize diverse sets of observations in an optimal way through the use of a state-of-the-art ocean GCM as dynamical interpolator, and taking into account prior knowledge of observational uncertainties and representation errors. In addition to providing statistically optimal estimates of the ocean state they enable diagnostics of quantities that cannot be directly measured (e.g., heat and volume transports), and provide a quantitative framework for assessing the impact of various observing systems in constraining the state estimate. While several projects are underway to provide such estimates for the Atlantic (and the global ocean), this report summarizes two projects that specifically target the issue of observation impact.

The first such project (Observing System Simulation Experiments for the Atlantic Meridional Overturning Circulation, led by Halliwell and Thacker) had as initial objectives to (1) build the hardware and software systems required to conduct Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs), (2) evaluate the suitability of different ocean models for performing these experiments, and (3) estimate the errors in ocean variables produced by present-day numerical models required to optimally perform data assimilation experiments. Targeted studies are under way to determine latitudes where cross-basin AMOC monitoring is particularly effective, and to quantify the improvement in AMOC representation achieved by extending Argo float sampling below 2000 m into the deep ocean.

The second project (Atlantic MOC Observing System Studies Using Adjoint Models, led by Wunsch, Heimbach, Ponte) is exploiting the adjoint model at the core of the ECCO state estimation tool to understand the Atlantic circulation. In the present context the impact of the various observations (satellite and in-situ), presently used or forthcoming, on target quantities such as meridional volume and heat transports are being investigated both via adjoint sensitivity calculations and via observation withholding experiments (OSEs). Transient spatial sensitivity patterns provide valuable information on the causal connection between changes in target quantities and remote perturbations. Several OSEs conducted reveal the strong complementarily between altimetry and Argo float observations. They also show that MOC estimates from hydrographic data alone are highly uncertain. Finally, both the sensitivity and the OSE studies underline the importance of the choice of metric in defining an optimal observing system strategy.

1.4 *Observing system design and planned enhancements*

1.4.1 South Atlantic: SAM (South Atlantic Meridional overturning circulation)

To date, most MOC observations have been focused in the North Atlantic, however model studies show that the South Atlantic is not just a passive conduit for the passage of water masses formed in other regions of the world ocean but instead actively participates in their transformation. Water mass transformations occur across the entire basin, but are intensified in regions of high mesoscale variability, particularly at the Brazil/Malvinas Confluence and at the Agulhas Retroflection. Models and observations also show that the South Atlantic plays a significant role in the establishment of oceanic teleconnections. For example, model results indicate that anomalies generated in the Southern Ocean are transmitted through inter-ocean exchanges to the northern basins. The Agulhas leakage influence reaches the northern hemisphere and models suggest that changes occurring in the South Atlantic alter the global MOC. These results highlight the need for sustained observations in the South Atlantic and in the choke points in the Southern Ocean, which, in conjunction with modeling efforts, would improve understanding of the processes necessary to formulate long-term climate predictions. Toward this end, planning for an observational program to measure the strength of the MOC as well as the meridional heat transport and the meridional fresh-water transport in the South Atlantic is underway.

As mentioned in section 1.1, an operational pilot program at 34.5°S serves as the beginning of this planned international program for the measure of the full-water-column, full-basin, meridional velocity, along with temperature and salinity at this latitude. Over the course of the past three years (2007-2010) three SAM workshops have been conducted to elucidate program goals and to establish international collaborators. Based on conversations at the three SAM workshops in 2007-2010, representatives from several countries indicated a willingness to provide ship-time for maintaining the planned array, including Argentina (Naval Hydrographic Service), Brazil (Naval Hydrographic Service), Russia (Shirshov Institute of Oceanography), South Africa (Univ. of Cape Town), and possibly the United Kingdom (National Oceanography Centre, British Antarctic Survey). As part of this effort, studies of prospective array types in a variety of ocean models have been ongoing. These tests suggest that 'geostrophic-style' mooring arrays are likely to provide very accurate transport estimates for calculating the AMOC. A brief report of implementation plans in progress for this program can be found in Appendix 4.

1.4.2 North Atlantic: OSNAP (Overturning in the Subpolar North Atlantic Program)

In order to assess the predictability of the AMOC and to determine its influence on climate, the carbon cycle, marine ecosystems and the cryosphere, a continuous record of the full-water column, trans-basin fluxes of heat, mass and fresh water carried in the AMOC is paramount. Though the U.K.-U.S. activity at 26^{o}N fulfills this requirement in the subtropical North Atlantic, studies over the past few years have made it increasingly clear that AMOC fluctuations are coherent only over limited meridional distances: break points in coherence occur at key latitudes, in particular at the subpolar/subtropical gyre boundary in the North Atlantic. Therefore, a transoceanic line in the subpolar North Atlantic that can measure the upper ocean heat, mass and freshwater fluxes and also capture the net contributions of the overflow waters from the Greenland-Iceland-Norwegian Seas to the AMOC, as well as that from the Labrador Sea, is a high priority. This measurement system would – in conjunction with the RAPID array – provide a means to evaluate intergyre connectivity within the North Atlantic. Importantly, this measurement system would allow for a determination of the role that deep water mass formation and export plays in the basin's overturning and associated poleward heat transport, assessments that currently have only been theorized and modeled, but not observed.

The design of OSNAP is driven by the overall goal to provide a continuous record of the full-water column, trans-basin fluxes of heat, mass and fresh water in the subpolar North Atlantic. Ancillary goals are to determine the connectivity of the waters in the lower limb of the overturning, to understand the dominant mechanism controlling overturning variability and to understand the impact of overturning variability on ocean biogeochemistry. Based on these goals, OSNAP is presently configured as trans-basin measurements that consist of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea, and the second from the southeast tip of Greenland to Scotland. Measurements along the trans-basin sections will consist of a mix of moorings, profiling floats, and gliders. Full-depth mooring arrays will be maintained at the boundaries. At this stage of planning, international collaborators include those from the UK, Canada and Germany. An OSNAP planning workshop was held at Duke in April of 2010. Two more workshops are planned for spring of 2011, both with a goal of establishing the observational design and the extent of the international partnerships. Studies of potential observational designs are ongoing, and an implementation plan for OSNAP is expected to be developed by late spring of 2011.

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

AMOC variability has been invoked to explain changes in climate around the Atlantic Basin and globally, particularly abrupt ones, on geological time scales (e.g., Rahmstorf, 2002; Denton and Broecker, 2008), motivating the study of its response to anthropogenic forcing and the interaction between natural variability and external forcing. However, a mechanistic understanding of the role of AMOC in modern global climate variability has not yet been elucidated. Specifically, changes in the AMOC have not yet been conclusively determined in the instrumental record, neither has its association with observed SST changes, which are known to drive climate variability, been determined. Therefore, an important objective of the US AMOC program has been to quantify the importance of the AMOC relative to other factors such as changes in surface forcing or other ocean circulation components in generating Atlantic SST variability and the role of the latter in global climate variability.

Climate model studies indicate that AMOC exhibits naturally occurring fluctuations in its intensity, which are leading to decadal-to-multidecadal SST variability (AMV). These SST fluctuations have been shown to contribute to significant global and regional climate variability. The impact of AMV was also detected in global-mean surface air temperature fluctuations on decadal-to-multidecadal time scales (Zhang et al., 2008; Thompson et al. 2009; Del Sole et al. 2011), with implications for the prediction of global mean surface temperature evolution in the coming decades. On a regional scale, there is even stronger support for the role of AMV. The basin wide multidecadal cooling and warming of the North Atlantic has been linked to the significant drop in Sahel rainfall in the 1970s and 80s and its subsequent recovery (Folland et al., 1986; Palmer et al., 1986; Knight et al., 2005 and 2006; Giannini et al., 2003; Held et al., 2005; Lu and Delworth, 2005; Zhang and Delworth, 2006), to the multidecadal variability in the number of Atlantic tropical cyclones (Landsea et al., 1999; Zhang and Delworth, 2006), North American droughts (Sutton and Hodson, 2005 and 2007), and as far as the Indian subcontinent and the summer monsoon season intensity (Zhang and Delworth, 2006).

The relationship between AMOC and AMV and the impact of the latter on climate variability continue to be the focus of AMOC-related studies in 2010. The achievements in this focus area by PIs involved in the US AMOC program are reported in more detail in the Appendix. These achievements include a model-based assessment of the impact of AMOC variability on Arctic surface air temperature and sea ice cover (Mahajan, et al., 2011). This study noted the association between the positive phase of AMOC and the recent decline in Arctic sea ice cover in the Labrador, Greenland, and Barents Seas. In this way, AMOC variability can enhance or diminish the impact of anthropogenic greenhouse warming and its effect on the Arctic. This study follows and reinforces several previous studies on the interaction between the Atlantic and the Arctic (e.g., Polyakov et al., 2004; Chylek et al., 2009).

Other works explore the atmospheric mechanisms linking the AMV to North and South American hydroclimate variability (Seager et al., 2010; Kushnir et al., 2010). Both these studies identified the tropical Atlantic region, which in observations varies in phase with the rest of the northern basin, as the key region for creating the remote impacts (consistent with the findings of Sutton and Hodson, 2005 and 2007). In this region SST variability leads to changes in convective activity and the effect on circulation is carried out of the region through tropical and extratropical planetary waves. Through these mechanisms the warm phase of the AMV leads to droughts both in the US West and northern Mexico and in southeastern South America, over southern Brazil, Uruguay, and Argentina. Related to the importance of tropical Atlantic SST and their association with AMOC variability, Wen et al. (2011) showed that the precipitation response to AMOC-induced SST change is highly nonlinear, suggesting that complex and competing atmosphere-ocean processes may be involved in the rainfall response to AMOC changes.

Finally, work reported in the 2010 AMOC PI meeting compared the impact of North Atlantic multidecadal SST variability (AMV) on precipitation and surface temperature over the globe in observations and in the multi-model ensemble of IPCC AR4 CGCMs. This study (Ting et al., in preparation) found a large degree of consistency in the prominent regional features. In particular, this work examined the multi-models depiction of AMV impacts in the pre-industrial, 20th and 21st century integrations to find that the impacts remain steady with the changing climate.

Almost all the impact studies mentioned above combine diagnostics of observations and model output, and as such help provide more robust definition and understanding of the impacts than available from the short instrumental record. We note that the summary of results provided above does not address all studies of AMOC/AMV impact, but only those achieved by PIs participating in this program.

3. *An assessment of AMOC variability mechanisms and AMOC predictability*

3.1 AMOC variability and mechanisms

Both at GFDL and NCAR, new sets of coupled simulations that use the most recent versions of the component models have been completed as part of their contributions to the IPCC AR5/CMIP5. These simulations are being analyzed jointly at GFDL (Delworth, Rosati, and collaborators), NCAR (Danabasoglu, Tribbia, and collaborators), MIT (Marshall and collaborators), and WHOI (Kwon and Frankignoul) with respect to their variability, particularly of AMOC, to identify robust variability mechanisms. The new version of the Community Climate System Model (CCSM4) shows much less overall AMOC variance than found in CCSM3 with only weak spectral peaks exceeding red noise at timescales longer than 50 years (Danabasoglu et al. 2011). At MIT, preliminary analysis of some of these simulations as well as of the MIT coupled model suggests that the pacemaker appears to be set in the subpolar basin of the Atlantic: variability in the AMOC of the subtropical gyre to the south lags that of buoyancy anomalies in the subpolar gyre by the time it takes a signal to be advected in the deep western boundary current. In addition to coupled model analyses, AMOC variability has also been assessed in a suite of historical ocean state estimations performed at NCAR. In particular, a 1948-2007 ocean-ice hindcast forced with atmospheric state fields exhibits a large upward trend in AMOC strength between 1960 and 2000 along with an associated AMV like surface temperature signature that compares well with observations.

At NCAR, work on identifying the mechanisms of AMOC variability in CCSM4 has focused on exploring the sensitivity of AMOC variability to model configuration and parameterizations. Yeager and Danabasoglu (2011) explain the damping effects of a Nordic Seas overflow parameterization on AMOC variance on decadal and longer timescales. To explore the robustness of this finding, GFDL has implemented this overflow parameterization in their model and sensitivity experiments are just now underway. One of the findings in the NCAR analysis is that the time series of AMOC maximum is not necessarily a good index for quantifying overall AMOC variability and associated spectral power. The sensitivity of AMOC variability to atmospheric resolution was also explored: in contrast to a similar comparison done using CCSM3, lower atmospheric resolution results in greater AMOC variability in CCSM4.

In addition to the coarser resolution climate models, GFDL has pursued the development of a new high-resolution model (GFDL CM2.5). This builds on the GFDL CM2.4 model by increasing the atmospheric resolution. Multi-century control and climate change simulations have been completed. Particular attention has been paid to the AMOC and its variability. The model shows significant multidecadal variability in the Greenland Sea, but only muted AMOC variability. This may be related to persistent biases in Labrador Sea convection (Delworth et al. 2011). In one aspect of this work, Farneti et al. (2010) have shown that oceanic mesoscale eddies play an important role in the response of the Southern Ocean to wind stress changes. GFDL is also developing GFDL CM2.6, a model with a 50 km atmosphere and a 4-10 km ocean.

In other study focusing on AMOC variability mechanisms, Kwon and Frankignoul (2010) at WHOI looked at the differences between the two regimes of AMOC variability that are seen in CCSM3, i.e. a period with very regular and strong decadal variability and one with irregular and weak multi-decadal variability, in terms of the mechanisms and associated global climate impact. They examined the latter weak multi- decadal regime which lacks significant multi-decadal spectral peak in the atmospheric forcing represented by the North Atlantic Oscillation, unlike the previously documented strongly decadal regime (Danabasoglu 2008). They found that the weak multi-decadal AMOC variability is an ocean-only mode associated with the advection of density anomalies driven by stochastic atmosphere around the subpolar gyre. The result also suggests that the slightly different strengths and extent of the subpolar gyre in the two regimes may be sufficient to result in two very different AMOC decadal variability regimes, leading to rapid transitions between the two.

Work at University of Miami (Dong and collegaues) has also focused on investigating seasonal to interannual variability in the AMOC and assess the sensitivity of results to model parameterizations and numerical algorithms. In this work, they are running two different global configurations of HYCOM at 0.72^{o} resolution for the 1948-2009 period.

Several projects have focused on idealized model studies to explore and isolate complicated mechanisms as complementary approaches to coupled model analysis. At MIT, 'toy models' have been developed based on delayed oscillator models for pacemaker regions. At UH, McCreary and colleagues used idealized model solutions forced only by a surface buoyancy flux to explore unresolved dynamical aspects of such base solutions. When the models include advection and mixing, solutions necessarily adjust to a steady state with an MOC. One of the most important processes for generating the MOC is dynamical adjustment along the eastern and western boundaries.

Similarly, Kamenkovich (UM) and Radko (NPS) continue to develop a conceptual understanding of key physical processes connecting AMOC and the Antarctic Circumpolar Current (ACC) using a combination of numerical simulations and theoretical analysis. Employing a suite of numerical simulations of AMOC in the global and Atlantic-only configurations, they demonstrated the fundamental importance of the ACC stratification in controlling the AMOC strength. Direct influence of the Ekman transport and eddy-driven heat/salt fluxes at the ACC-Atlantic boundary has a secondary importance (Kamenkovich and Radko 2011). Numerical simulations of the AMOC response to a North Atlantic freshwater anomaly demonstrate that a delay in ACC response to such forcing acts to destabilize AMOC and amplify weakening of the AMOC strength. They also developed an analytical model of the Atlantic deep stratification and AMOC in order to illustrate the dynamics of the ACC-Atlantic coupling. The model predicts the stratification and meridional transport as a function of the mechanical and thermodynamic forcing at the sea-surface (Radko and Kamenkovich 2011). This analytical model demonstrates that the mean stratification of the lower thermocline is determined by the surface forcing in the ACC and, to a lesser extent, by the North Atlantic Deep Water formation rate; the overall effect of diapycnal mixing on the net stratification is surprisingly limited.

To understand the warm branch of the meridional circulation of the Atlantic Ocean, particularly between the warm subtropics and the cold subpolar gyre, Hakkinen and Rhines (2009; 2010) combined altimetric surface height and the subsurface circulation as represented in the SODA ocean assimilation model. This has led to strong support for the hypothesis that the warming and salinity increase in the northern Atlantic during the past decade is through the opening of exchange pathways between subtropical and subpolar regions. Tracking tracers and particles while coordinating with surface eddy energy from satellite altimetry and earlier surface drifter analysis, leads to a pattern of enhanced flow from the Gulf Stream directed northward to high latitude. This in turn connects with the gyre circulation, which was earlier identified as the principal variability of the upper North Atlantic during the satellite altimetry era.

Kelly, Thompson, and colleagues at UW analyzed the heat budget in the Gulf Stream and the North Atlantic Current using four different modeling systems, showing that upper ocean heat transport convergence drives the heat budget in both regions with surface heat flux a much smaller contributor on interannual time scales.

In another study related to heat transport, GFDL, NCAR, and UM (W. Johns) compared a variety of CCSM4 and GFDL simulations to estimates of meridional heat transport (MHT) at 26.5^{o}N from the RAPID mooring array. It is found that model underestimation of MHT at this latitude is due to too weak geostrophic gyre transport because of biases in temperature structure along the western boundary (Msadek et al. 2011).

3.2 AMOC prediction and predictability

Several prediction studies have been undertaken at GFDL. In order to establish credibility of the decadal predictions, hindcasts must be run so that the prediction system may be validated. The temporal inhomogeneity of the ocean observing system makes the verification a challenge. Using the present-day observing system of ARGO and altimetry, Chang et al. (2010) constructed basis functions for the global temperature and salinity relationship so that it is possible to go back to 1993 with XBT data and construct corresponding pseudo salinity profiles. This allowed for a better initialization and verification of the decadal hindcasts from 1993-2002. In related work, Msadek et al. (2010) completed a perfect predictability study of the AMOC in GFDL CM2.1 probing characteristics of the predictability related to subsurface temperature and sea level height. GFDL also completed two suites of prototype decadal hindcasts and predictions, each over 4000 model years. The predictive skill in the hindcasts is being investigated.

In support of their decadal prediction work, NCAR has developed an ocean data assimilation capability based on the Data Assimilation Research Testbed (DART) to obtain ocean initial conditions. This endeavor was in collaboration with GFDL and J. Anderson (NCAR). A suite of fully coupled decadal prediction runs have been integrated following the CMIP5 experimental protocol using ocean initial conditions obtained from this DART assimilation as well as from forced ocean-ice hindcasts. The AMOC evolution in initialized decadal prediction experiments differs significantly from that in uninitialized scenario runs, but useful predictive skill associated with this full-field ocean initialization method remains to be demonstrated.

Zhang at GFDL studied the meridional coherence of AMOC variations and the northward intensification of anthropogenically forced AMOC changes in density space using the GFDL CM2.1 coupled climate model. It is found that AMOC variations propagate with the advection speed from Flemish Cap to Cap Hatteras, resulting in a several-year time lead between subpolar and subtropical AMOC variations and providing a more useful predictability with AMOC variations showing significant meridional coherence in density space (Zhang 2010a). Furthermore, the anthropogenically forced AMOC weakening over the 21st century is found to be larger at northern high latitudes (about 50%, nearly twice of those at lower latitudes) due to changes in the NADW formation. In contrast, anthropogenically forced AMOC changes are much smaller in depth space at the same northern high latitudes. Hence projecting AMOC changes in depth space would significantly underestimate AMOC changes associated with changes in NADW formation (Zhang 2010b).

To complement above dynamical studies, Mahajan at NRNL and collaborators at GFDL developed a statistical predictive model of AMOC variability based on the observed subsurface temperature (Tsub) and sea surface height (SSH) fingerprints of the AMOC (Mahajan et al. 2011). In this work, a statistical model is fit to the leading mode of objectively analyzed, detrended North Atlantic Tsub anomalies (1955-2003) and is applied to assimilated Tsub and altimetry SSH anomalies to make predictions. The statistical model predicts a weakening of AMOC strength in a few years after its peak around 2005. A similar statistical model, fit to the time series of the leading mode of modeled Tsub anomalies from the GFDL CM2.1 control simulation, is applied to predict modeled Tsub, SSH, and AMOC anomalies. The two models show comparable skills in predicting observed Tsub and modeled Tsub, SSH, and AMOC variations.

C. NEAR-TERM RESEARCH PRIORITIES

The following near-term research priorities were identified in discussions at the 2010 annual U.S. AMOC science meeting (Miami, FL; June 7-9, 2010):

1. *Observing system implementation and evaluation*

Assessing the meridional coherence of changes in the overturning remains a challenging observational requirement. Although the RAPID array continues to provide observations in the tropics and Argo and altimetry have been used to estimate overturning variability at mid-latitudes in the North Atlantic, observing system enhancements are needed to provide estimates of overturning variability in the subpolar North Atlantic as well as in the South Atlantic. The OSNAP program will capture overturning variability in the subpolar N. Atlantic, near the source regions for the North Atlantic Deep Water. The SAMOC program will provide observations in the South Atlantic. These will allow researchers to address questions such as: Do changes in the overturning originate in the deep-water formation regions, or do other mechanisms drive changes in overturning strength? How fast do such changes propagate throughout the Atlantic? Addressing these questions is clearly necessary to improve understanding of the role of the overturning in regulating regional and global climate—a prerequisite to predicting future AMOC behavior in a warming climate. In addition to the meridional coherence of the overturning circulation itself, better characterization of the large-scale forcing is also needed. For instance, ocean vector wind observations have recently suffered due to severe degradations in the QuikSCAT satellite. Such observations are important both for accurate simulations as well as observational estimates of AMOC variability.

At present, Argo, the primary component of the broadscale global ocean observing system for temperature and salinity samples only the upper 2000 meters of the oceans. In many regions, this covers only the upper half or so of the southward flowing North Atlantic Deep Water. The importance of sampling temperature and salinity changes in deep oceans remain unclear. How sensitive are ocean simulations (that assimilate data or otherwise) to these deep property changes? Simulation efforts are needed to test the importance of deep-water observations for constraining ocean model. Such work will provide guidance for building the deep ocean observing system by providing estimates for how many and what types of deep observations (deep Argo floats, or full depth gliders) are needed.

Numerous estimates of overturning variability are available from ocean state estimation models. However, 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.

Although sinking in the high-latitude oceans has long been recognized as a key part of the overturning circulation, significant uncertainty remains about the complex processes that lead to deep-water formation. In particular, which physical processes must be included in order to accurately simulate the formation and southward spread of North Atlantic Deep Water? What observations are needed to constrain simulations such that they produce the correct volume, temperature and salinity of deep water? Answering these questions will require a coordinated effort that includes both model development and observing system sensitivity studies. Further work is needed not only to understand the ocean processes, but also the air-sea interaction that gives rise to the deep-water formation. Further work is needed to validate surface flux products and to understand their accuracies and biases. In situ data from buoys and comprehensive process studies such as CLIMODE will be necessary to develop flux estimates with sufficient accuracy.

Because the overturning plays such an important role in determining the oceanic heat transport of the Atlantic, it is expected that changes in overturning strength will manifest in patterns of sea surface temperature, or perhaps sea surface height, or salinity. If such links can be rigorously established, they would provide a means to evaluate overturning strength in the era before direct instrumental observations of the overturning became available. These so-called fingerprints exist in some coupled climate model simulations, but further work is needed to determine whether these patterns are representative of the actual AMOC and if so, to determine the extent to which the historical data allows the overturning strength to be reconstructed.

2. *AMOC climate impacts*

Understanding the link between AMOC and SST variability

A crucial issue regarding the impact of AMOC on the global climate system as well as its predictability is the link between its variability and upper ocean temperatures, in particular SST. This is because such link enables AMOC variability to impact the atmosphere. It is therefore important to focus part of the effort in this research program on better defining and understanding the interaction between AMOC variability and the variability of upper ocean properties: SST, salinity, and heat content. Locally, the interplay between the ocean and the atmosphere consists of a two-way interaction. As the atmosphere responds to AMOC variability it affects the latter. This is conceivably an important ingredient of the variability and a fundamental factor in AMOC predictability. Therefore, more study of this interaction is warranted.

2.1 Understanding the mechanisms of teleconnections between AMOC/North Atlantic SST and climate variability elsewhere

Determining and understanding the nature and mechanisms of AMOC influence on SST and subsequently the impact on the atmospheric circulation is important for understanding and attributing past climate variability and building future (near-term) climate predictions on a robust foundation. Previous studies detected connections between Atlantic SST variability, possibly due to the AMOC, and climate variability in the continents and ocean basins surrounding the North Atlantic. We need to better identify the source of these impacts and the mechanisms that govern the atmospheric teleconnections that enable them. Such research would benefit from a comparison between AMOC impacts and those of other long-term changes in climate, forced and natural. Most such studies have so far have used a combination of model integrations and analysis of instrumental observations. Such work should continue. However, only few studies extended the work to include the use the paleo-climate record. Such studies should be expanded to address the need for longer data records and thus build more robust understanding of the impacts and more trust in the models.

2.2 Other impacts of AMOC

AMOC variability impact on ocean ecosystems, sea level changes around the Atlantic Basin, and importantly, the exchange of carbon between the atmosphere and ocean are also highly relevant. To assure a well-balanced research program that addresses all the challenges posed by the AMOC the program should therefore encourage and support studies in these areas.

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

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

2.4 Strengthen links to other related CLIVAR/WCRP activities

This will raise the profile of U.S. AMOC research and help in exchange of important information and stimulate progress. This goal can be achieved through U.S. CLIVAR, the International CLIVAR Atlantic Implementation Panel, and through communication with individual program committees, nationally and internationally.

3. *AMOC mechanisms and predictability*

3.1 Assessment of the various proposed mechanisms

Numerous mechanisms have been proposed to explain the AMOC variability in decadal to centennial time scales simulated in many different numerical models. However, it is not yet clear which mechanisms are more relevant to observed variability and how much each mechanism is dependent on specifics of each model. The biggest barrier towards answering these questions is perhaps limited available observational information to compare with and assess against the modeling results.

Therefore, we need to develop new observations and synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational information. This effort should be carried in close collaboration with the program objective I "The design and implementation of an AMOC monitoring system". It is desirable to identify standard set of metrics that can be used to assess the simulated AMOC variability and mechanisms against the available observations.

At the same time, parallel efforts should be invested in understanding the model dependencies of the proposed AMOC mechanisms. To address this issue, a focused comparison study for the AMOC mechanisms should be coordinated among the modeling groups. In addition, more resources should be invested in exploring impacts of various model biases, e.g., too zonal Gulf Stream and North Atlantic Current paths evident in most of the state-of-the-art global coupled climate model simulations, on AMOC variability and also on predictability. With the recent development of eddy-resolving high resolution, i.e., 0.1° or higher resolution, ocean models, it is also important to investigate dependency of AMOC variability and its mechanisms on the model resolution and the impact of mesoscale ocean dynamics on the AMOC variability.

The ocean meridional heat transport (MHT) in the North Atlantic at various latitudes can be used as a target variable to address the above two issues. The MHT 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. Therefore, one focused way to address both of the above issues is to explore AMOC and MHT relationships in various models (forward, assimilation, non-eddy-resolving, eddy-resolving) in comparison with the RAPID data and understand the reasons for differences or biases in the relationship between model AMOC intensity and MHT in available models, as compared to observations.

3.2 Examining robustness of AMOC predictability

Significant progress has been made in the past couple of years in AMOC predictability and decadal prediction research led by climate modeling centers in U.S. and around the world as summarized in section B. As in the case with the mechanisms of the AMOC variability discussed above, it is time to invest resources to assess the robustness and model dependency of various results and proposed methods.

As the modeling centers are conducting near-term prediction experiments for the IPCC AR5, an inter-comparison study of these simulations should be performed to investigate robustness of predictions among simulations using various models. In addition, more controlled experiments should be coordinated among the modeling groups to further understand the model dependencies. For example, inter-comparison of hindcast ocean-only and ocean-ice coupled simulations forced with the same atmospheric (Coordinated Ocean-ice Reference Experiments, CORE) data sets would be valuable to assess the robustness of model simulations under a common forcing.

A consensus rising from various decadal prediction studies is that the initialization is one of the biggest sources of uncertainty. Therefore, focused efforts should be made to identify the "best" initialization practices for decadal prediction simulations. In addition, to assess the robustness of the decadal prediction and AMOC predictability studies, we should identify standard set of metrics that can be commonly applied to various model-based results. Ocean state estimate and assimilation researches associated with the program objective I "The design and implementation of an AMOC monitoring system” should be also integrated into these efforts. Finally, these efforts should seek collaboration with the U.S. CLIVAR Decadal Predictability Working Group as well as the International CLIVAR Working Group on Ocean Model Development and Global Synthesis and Observational Panel.

D. RELATED ACTIVITIES TO SUSTAIN

1. Required large-scale observations

A number of research questions identified in the Implementation Plan can be addressed by analysis and synthesis of data from elements of the large-scale sustained observing system, including current and proposed satellite and in-situ observational platforms (e.g., ARGO). The primary responsibility for the design and implementation of these observing systems lies with NASA, NOAA, NSF and international partners and requires resources above those that can be explicitly provided by the US AMOC Program. The Oceanobs09 Conference (www.oceanobs09.net), Venice, September 2009, provides a tremendously comprehensive description of the current sustained ocean observing system and plans for the next decade. The Argo observing system is at its full planned strength. The continuity of U.S. climate satellite observations is problematic: many planned measurement systems have been cancelled or delayed. The European research and operational programs are more robust overall. The status and progress (or lack thereof) of specific measurements are listed below.

a) *Air-sea fluxes: heat, momentum and freshwater*

- Surface Vector Winds: Surface Vector Winds: QuikSCAT stopped collecting vector wind measurements towards the end of 2009 after 10 years of successful operation (8 years beyond its designed lifetime. The US NPOESS sensor for wind vectors was cancelled. The prospect of launching a new US scatterometer is not encouraging due to budgetary constraints. ESA has an operational scatterometer (ASCAT on MetOp) with somewhat less coverage and accuracy. The Indian space agency has recently launched an experimental scatterometer, and another one is expected to launch from China in a few years. However, these instruments do not provide the same spatial resolution or sensitivity to high winds as QuikSCAT. Furthermore, it is unknown whether all data from these will be made available.
- Precipitation: TRMM has provided surface precipitation and the vertical profile of precipitation over the tropical ocean since 1997. The follow-on, NASA's Global Precipitation Measurement (GPM), will have global coverage, the core spacecraft of which is scheduled to be launched in 2013. It will provide improved measurements of solid precipitation (snow) and rainfall over land.
- SST: Microwave sensor AMSR-E on Aqua is operational. A follow-on sensor to obtain microwave (near all-weather) SST on NPOESS was cancelled and no replacement for AMSR-E has been funded. However, AMSR2 is planned for launch in 2011 aboard GCOM-W1 (Japan). MODIS sensors on Aqua and Terra platforms are operational. NPOESS Preparatory Project (NPP) is scheduled for launch later this year and will have the VIIRS sensor that contains similar infrared bands as MODIS.
- The International Satellite Cloud Climatology Project (ISCCP) has been collecting and calibrating the infrared and visible radiances obtained from imaging radiometers carried on the international

constellation of weather satellites since 1983. Its data have been widely used for estimating ocean surface radiative heat fluxes because of the frequent sampling of the geostationary sensors. The coarse spatial and spectral resolutions of geostationary sensors could be improved with sensors from polar orbiters, such as the Clouds and the Earth's Radiant Energy System (CERES) Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua missions, which were launched in 2000 and 2002 respectively.

b) *Oceanic heat, freshwater and mass transport and storage*

- Sea level and ocean velocities: Jason-2 was launched in June 2008 and Jason-3 is anticipated for launch in 2013, providing continuity of the sea surface height record begun by TOPEX/Poseidon in 1992. SWOT (a wide-swath altimeter concept for sea level and surface water) is anticipated to be launched in 2019. The drifting surface buoy network achieved its GCOS target of 1250 buoys, however the goal of uniform buoy density in the oceans has not been achieved (e.g. Atlantic region) and will require more drifters than the 1250 target figure. Global sea level measurements (part of GCOS) received increased attention after the Indian Ocean tsunamis and more stations were added in this region and also in greater Africa.
- Heat storage: ARGO has reached its goal of 3000 floats globally and needs to be sustained. High-resolution XBT data continues to be collected along 18 lines. Low-density lines have been scaled back in favor of Argo. (See sea level above for altimeter status.) Historical XBT observational biases related to estimates and/or corrections of fall-rate equations continue to be addressed by at least three different efforts worldwide.
- Salinity: Launch of the Aquarius/SAC-D mission has been postponed beyond mid-2011. The European SMOS mission has begun to provide some space based observations of surface salinity, however validation of these data are still needed to assess their accuracy. (See Heat Storage for Argo status).
- Mass budgets: GRACE is operational and a follow-on mission is being pursued, and is expected to launch in 2016. However, given its age, it is likely that there will be a gap between GRACE and its follow-on due to. ESA's GOCE mission was launched in March 2009 and should improve geoid knowledge at scales less than 200km. A preliminary data set has been released including 3-months of observations from GOCE and estimates of the dynamic topography based on these data look promising.

c) *Freshwater boundary inputs*

- Ice cover, advection and melt: An ICESAT 2 follow-on has been funded for further study (tentative launch in late 2015). ESA's Cryosat 2 was launched in April 2010 and began producing science data in November (sea ice thickness and ice sheet topography as well as ocean topography in the Arctic).
- Discharge from rivers: Studies continue regarding using altimeters to quantify river discharge.

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 is of central importance to the US AMOC goals. In order to identify "fingerprints" of AMOC variability on decadal and centennial scales:

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

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

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

d) Multiproxy studies are needed. No single paleo proxy measurement is sufficient to recreated ocean circulation changes. Combinations of measurements on the same samples are required for robustness.

3. *Modeling capabilities*

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

A wide variety of models are in use today. They range from very simple box models of the AMOC, to fully complex three dimensional high resolution coupled models. Maintaining such a hierarchy of models is vital to increasing our understanding of the AMOC. These activities require:

a) Sustained support for the high end coupled modeling activities at the large US national laboratories, including NCAR and GFDL. These activities are limited by available US supercomputing power for climate studies.

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

c) Support for the infrastructure that makes climate model output easily available over the Web. A vast body of model output from the IPCC Fourth Assessment Report (AR4) is available on the Web (https://esg.llnl.gov:8443/home/publicHomePage.do), and this model output is important for a suite of AMOC studies. In particular, future modeling output from the IPCC Fifth Assessment Report (AR5) that will be made publicly available includes prediction experiments with strong AMOC relevance. It is vital that scientists studying AMOC variability and predictability have open access to such model output from state of the art coupled models.

d) Sustained efforts are needed to improve ocean data assimilation systems used to estimate the AMOC state in the past few decades. There remain substantial differences in the estimated variability of AMOC state derived from the current generations of assimilation products, especially on decadal time scales. While the lack of observations in past decades contributes to these differences, the limitation in understanding model and data errors (which dictate the outcome of the assimilation) is also an important factor. Continuing efforts to improve the representation of the model and data errors of these systems can lead to better consistency and fidelity of the resultant estimation products, which would greatly enhance the potential of using these products to study the mechanisms of AMOC variability. Studies that demonstrate the relative impact of existing observations in constraining the estimated AMOC state should be encouraged and augmented. Such efforts would be complementary to the projects that are already funded to study the optimal design of AMOC observing systems. Support is also needed for employing ocean data assimilation systems to examine the potential impact of having full-depth measurements via ARGO floats on estimating AMOC states. Data assimilation systems not only offer a potential tool to study the variability and mechanisms of the AMOC, but important to predictability and prediction studies as well. CLIVAR has recognized the need to initialize decadal prediction using data assimilation products. The impact of observationally constrained initial states (from assimilation products) in different time periods (e.g., the WOCE era, the altimetry era, and the Argo era) on the predicted AMOC state can illustrate the effects of the maturing observing systems (e.g., with the built-up of the data volume from altimetry, Argo, and RAPID) on AMOC prediction.

The sustained support for assimilation efforts should not be limited to ocean data assimilation. The coupled nature of the ocean-atmosphere system demand a coupled approach towards state estimation. There are already emerging efforts for coupled ocean-atmosphere data assimilation used to study AMOC. Such efforts complement the projects already funded under AMOC for ocean model-based synthesis and observing system design studies. Although not currently funded under AMOC, these efforts should be sustained and augmented in the future.

e) While model-based (modeling and assimilation) studies of the AMOC have yielded – and continue to yield – important insights into AMOC behavior, we know that the AMOC is influenced by processes on scales much smaller than are represented in modeling studies today. For example, the recent IPCC AR4 assessment report used state of the art climate models that had oceanic resolution of approximately 1 degree (100 Km) in the horizontal direction. We know that such models are unable to represent a host of processes involved in the AMOC, including oceanic mesoscale eddies, bottom flows over sills, intense western boundary currents, and small-scale oceanic convection. For example, among the IPCC AR4 climate models, a common modeling bias in the North Atlantic is that the separation of the Gulf Stream from the coast occurs too far north and the North Atlantic Current (NAC) does not penetrate northwest, but moves too further eastward, resulting in a warm SST bias south of the Grand Banks and a large area of cold SST bias east of Newfoundland. Our understanding of the AMOC and its sensitivity to climate change is therefore predicated on a class of models that are unable to represent what may be crucial components of AMOC variability and its response to changing radiative forcing. For example, our assessment of the likelihood of rapid or abrupt future changes in the AMOC is based on models that do not include potentially crucial processes. While the predictions from these models may well turn out to be accurate, the lack of correct representation of many crucial processes forms an important caveat to our ability to assess and predict the future behavior of the AMOC

There is movement in US modeling towards higher resolution ocean-only and ocean-atmosphere coupled models, but this movement is greatly inhibited by the computing available to climate researchers today. This may be a key rate-limiting-step toward improved modeling capabilities for the AMOC. Sustaining and substantially augmenting computing resources for simulation and prediction of the AMOC is a high priority.

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, and continued support for such studies is vital. Some of these important processes include the influence of topography on oceanic flows, the representation of oceanic convection and mixing, 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 those into state of the art climate models, are crucial.

E. FUNDING

1. *FY10 project totals*

While $40M was requested for all four of the Ocean Research Priorities Plan Near-term Priorities in FY09, funding bills passed by Congress, and budgetary decisions within agencies resulted in substantially less than anticipated new funds being made available for implementation of new activities. However, federal research agencies contributed in excess of $10 million in support of AMOC activities. There are now 40 funded AMOC projects (Appendix 1) sponsored by federal research agencies. NASA provides over $1.8M in funding to competed projects that exploit NASA (in conjunction with other) assets and for characterizing variability of AMOC and its key attributes. Although NOAA did not receive its entire requested budget increase for AMOC, it allocated more than $1.5M for new activities in AMOC modeling, synthesis, and predictability studies, and continues to provide about $1M for targeted AMOC observations and monitoring. NSF supports AMOC through greater than $6.2M of investment for a variety of activities. Lastly, DOE is supporting a few projects addressing modeling and variability of AMOC in the context of climate change.

2. *FY11 and beyond*

NOAA solicited AMOC-related proposals for FY11. NSF continues to encourage submission of AMOC proposals for consideration. NASA also considers AMOC-relevant proposals. Congress has not yet approved appropriations for the federal research agencies for FY2011. Thus, agencies will not know their actual budgets until well into 2011. After Congressional approval is gained, agency internal allocation decisions will determine actual spending levels for AMOC. The Ocean Research Priorities Plan Near-term Priorities, including AMOC, remains an Administration/OSTP budget priority in FY11.

F. SUMMARY

Legacy and recently-funded projects have been molded into a U.S. interagency program focused on the

Atlantic Meridional Overturning Circulation in an effort to address the 4th near-term priority of the administration's Ocean Research Priorities Plan. Significant momentum is building within this program, despite the reduced funding levels committed to the program with respect to that originally intended. In particular, funding limitations have delayed key parts of the implementation plan, among them the initiation of trans-basin monitoring systems at other latitudes to complement the RAPID-MOCHA system deployed at 26.5°N.

Annual program meetings, held either independently or jointly with the U.K. RAPID annual meetings, have been very successful in bringing together the program PIs to share research results, develop collaborative projects, and identify near-term research priorities. Research highlights and accomplishments of the program are reviewed within the body of this document, as are the main research priorities resulting from discussions at this year's Miami annual meeting. Going forward to 2011, the program recommends that:

1. Assessing the meridional coherence of AMOC changes should be a continued focus of prognostic models, state estimation models, and enhancement of the AMOC observing system. The design of monitoring systems for the time varying strength of the AMOC in the subpolar North Atlantic and subtropical South Atlantic should be completed this year and implemented during 2012. The importance of deep temperature and salinity measurements (i.e. deep ARGO) in monitoring AMOC variability should also be assessed.

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

3. Studies aiming to develop fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations should be further encouraged and supported. Particular focus should be on understanding the linkage between AMOC variability and SST variability, both from a diagnostic and mechanistic viewpoint.

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

5. Further effort needs to be directed toward understanding AMOC variability mechanisms and the model dependencies of these variability mechanisms. To address this issue, a detailed comparison study for the AMOC mechanisms should be coordinated among modeling groups. A focused effort is also needed to develop a synthesis of existing observations, including synthesis of proxy data, to discriminate various model-based proposed mechanisms against the observational data.

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

7. In coordination with the near-term prediction experiments being conducted by modeling centers for the IPCC AR5, an inter-comparison study should be performed to investigate the robustness of AMOC predictions among simulations using various models. These efforts should seek collaboration with the U.S. CLIVAR Decadal Predictability Working Group as well as the International CLIVAR Working Group on Ocean Model Development and Global Synthesis and Observational Panel.

Finally, it is recommended that FY12 investments be ramped up to at least to the levels originally envisioned for FY08 so that all urgent activities as described in the AMOC Implementation Strategy can be pursued.

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Appendices:

Appendix 1. AMOC Projects currently underway or recently funded.

Proj. #	**Principal Investigator**	**Co-PIs**	**Project Title**	**Sponsor**	**Duration**
1	M. O. Baringer (NOAA.AOML)	S. L. Garzoli, Gustavo Goni, Carlisle Thacker, Claude Lumpkin (NOAA/AOML)	Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean	NOAA	2006 - ongoing
2	M. O. Baringer (NOAA/AOML)	C. S. Meinen, S. L. Garzoli (NOAA/AOML)	Western Boundary Time Series (WBTS)	NOAA	1/2000 - ongoing
3	Amy Bower (WHOI)		A Crossroads of the Atlantic Meridional Overturning Circulation: The Charlie-Gibbs Fracture Zone	NSF	9/2009
4	James Carton (U. Maryland)	Benjamin Giese (Texas A&M U.)	SODA: exploring centennial changes in ocean circulation	NSF & NOAA	6/2008 – 5/2011
5	P. Chang	R. Saravanan and R. Zhang	Towards an Understanding of the Role of the Atlantic Thermohaline and Wind-driven Circulation in the Tropical Atlantic Variability (TAV)	NSF	2006 – 2008
6	Ruth Curry		An Investigation of Abyssal Mixing and Interior Transports in the North Atlantic	NSF	10/2009
7	Tom Delworth (GFDL)	A.J. Rosati	Decadal Climate Predictability and Predictions - Focus on the	NOAA	5/2007 - 4/2010

			Atlantic		
8	Kathleen Donohue (URI)	C.Flagg (Stony Brook Univ) and T. Rossby (URI)	The Oleander Project: Sustained observations of ocean currents in the NW Atlantic between New York and Bermuda	NSF	1993-2008, 2008-2013 (funding increment)
9	George Halliwell (U Miami)	W. Carlisle Thacker (NOAA/AOML)	Observing system simulation experiments for the Atlantic meridional overturning circulation	NOAA	8/2008 – 7/2011
10	Gordon Hamilton (University of Maine)	F. Straneo (WHOI), L. Stearns (U Kansas), D. Sutherland (UWash)	Collaboative Reserch: Glacier-Ocean Coupling in a Large East Greenland Fjord	NSF-OPP	8/2009 - 7/2011
11	B. Johns (U. Miami)	M. Baringer, C. Meinen (NOAA/AOML) and L. Beal (U. Miami)	An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic	NSF & NOAA	4/2003 – 1/2008; renewed 1/2008 – 1/2014
12	Terry Joyce (WHOI)		Circulation and Variability in the Mid-Latitude N. Atlantic Ocean	NSF	9/2002 - 2005;
13	Igor Kamenkovich		Collaborative Research: Studies of the Influence of the Antarctic Circumpolar Current on the Atlantic Meridional Circulation	NSF	7/2007 - 9/2010
14	K. A. Kelly (U. Washington)	L. Thompson (U. Washington)	(1) Assessing Meridional Transports in the North Atlantic Ocean (2) The Contribution of Ocean Circulation to North Atlantic SST	NASA	10/2008 – 9/2012
15	Craig M. Lee (U. Washington)	Dick Moritz, Jason Gobat (U. Washington); and B. Petrie (Bedford Inst.)	An Observational Array for High-Resolution, Year-Round Measurements of Volume, Freshwater and Ice Flux Variability in Davis Strait	NSF	4/2007 – 3/2009
16	Tong Lee (JPL)	Geoffrey Gebbie (Harvard U.)	Variability and Forcing Mechanisms of the Atlantic Meridional Overturning Circulation	NASA	9/2008 – 8/2011
17	Jonathon Lilly	Thomas Rossby, Fiammetta	Collaborative Research: Mode Water Formation in the	NSF	6/2009 –

		Straneo	Lofoten Basin: A Key Element in the Meridional Overturning Circulation		
18	W. Timothy Liu (JPL)	Xiaosu Xie (JPL)	Evaluation of Meridional Transport of Water and Heat in the Atlantic Ocean Using Satellite Data	NASA	10/2007 – 9/2010
19	S. Lozier (Duke)	A. Bower (WHOI)	Export Pathways from the Subpolar North Atlantic: Phase Two	NSF	3/2008 – 3/2011
20	Julian McCreary		Dynamics of the descending branch of the Atlantic Meridional Overturning Circulation	NSF	6/2009 –
21	Vikram Mehta		A Diagnostic Study of the Interannual to Decadal Variability of the Tropical Atlantic Sea-surface Temperatures Using Satellite Remote Sensing Based and ECCO-assimilated Oceanographic Data Products	NASA	2008
22	C. S. Meinen (NOAA/AOML)	S. L. Garzoli, M. O. Baringer (NOAA/AOML); A. Piola2, A. Troisi (SHN); E. Campos (IOUSP); M. Mata (FURG); and S. Speich (IFREMER)	South Atlantic MOC (SAM)	NOAA	10/2008 - 2012
23	Peter Minnett (U. Miami)	Chelle Gentemann (Remote Sensing Systems, Inc.)	AMOC: Focused analysis of satellite data sets	NASA	8/2008 – 7/2011
24	P.B. Rhines (U. Washington)	S. Häkkinen (NASA GSFC)	Pathways of meridional circulation in the North Atlantic Ocean	NASA	10/2008 – 9/2012
25	Peter Rhines		Deep ocean mixing and circulation in subpolar seas	NSF	6/2009
26	Uwe Send (Scripps)		Meridional Overturning Variability Experiment (MOVE)	NOAA	2006-2010
27	CK Shum		Satellite Monitoring of the Present-Day Evolution of the Atlantic Meridional Overturning Circulation (AMOC)	NASA	2009-2012
28	Fiamma Straneo	S. Lentz	From rivers to the ocean: the	NSF-OCE	1/2009 -

	(WHOI)		dynamics of freshwater export from Hudson Strait		12/2012
29	J. Toole (WHOI)	R. Curry, T. Joyce, M. McCartney (WHOI); W. Smethie, Jr (LDEO); J. Smith (Bedford Inst.)	Line W: A sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39oN	NSF & WHOI	5/2003 – 2/2008; renewed 2/2008 – 12/2013
30	Josh K. Willis (JPL)		Monitoring the Atlantic Meridional Overturning Circulation using a combination of SST, altimeter, and Argo data	NASA	10/2008 – 9/2010
31	Carl Wunsch (MIT)	Patrick Heimbach (MIT) and Rui Ponte (AER, Inc.)	AMOC observing system studies using adjoint models	NASA	8/2008 – 7/2011
32	Xiao-Hai Yan (U. Delaware)	Young-Heon Jo	Satellite Multi-Sensor Studies of Deep Ocean Convection in the North Atlantic Ocean	NASA	2009-2013
33	Jiayan Yang		Atmospheric Forcing of Marginal-Sea Overflows	NSF	9/2009
34	Gokhan Danabasoglu (NCAR)	Joseph Tribbia (NCAR), Tom Delworth (GFDL), Tony Rosati (GFDL), John Marshall (MIT)	A Collaborative Investigation of the Mechanisms, Predicability, and Climate Impacts of Decadal-scale AMOC Variability Simulaed in a Hierarchy of Models	NOAA	9/2009 - 2012
35	Michael McPhaden (NOAA PMEL)	Dongxiao Zhang (UWash) and Wei Cheng (UWash)	Decadal and Multidecadal Variability of the AMOC in Observational Records and Numerical Models	NOAA	5/2010 – 4/2013
36	Young-Oh Kwon (WHOI)	Claude Frankingoul (WHOI), Gokhan Danabasoglu (NCAR)	Decadal Variability of the Atlantic Meridional Overturning Circulation and Its Impact on the Climate: Two Regimes and Rapid Transition	NOAA	5/2010 – 4/2012
37	Patrick Heimback (MIT)		Sensitivity Patterns of Atlantic Meridional Overturning and Related Climate Diagnostics over the Instrumental Period	NOAA	5/2010 – 4/2013
38	Shenfu Dong (NOAA)	Gustavo Goni, Molly Baringer, George Halliwell (NOAA AOML)	Assessing the Sensitivity of Northward Heat Transport/Atlantic Meridional Overturning Circulation to Forcing in Existing Numerical	NOAA	5/2010 – 4/2013

			Model Simulations		
39	Rong Zhang (NOAA)	2. Salil Mahajan (Oak Ridge National Lab, Oak Ridge, TN), Tom Delworth, Shaoqing Zhang, Tony Rosati (GFDL/NOAA, Princeton, NJ) 3. Salil Mahajan, Tom Delworth	1. Latitudinal Dependence of Natural Variations and Anthropogenically Forced Changes in the Atlantic Meridional Overturning Circulation (AMOC) 2. Predicting the Atlantic Meridional Overturning Circulation (AMOC) Variations Using Subsurface and Surface Fingerprints 3. Impact of the Atlantic Meridional Overturning Circulation (AMOC) Variability on Arctic Surface Air Temperature and Sea-Ice Variability	NOAA	2010 – 2013
40	Sarah Gille (University of California - SIO)	Douglas Martinson (Columbia University, LDEO)	Assessing Unstoppable Change: Ocean Heat Storage and Antarctic Glacial Ice Melt	NOAA	5/2010 – 4/2013

APPENDIX 2. Recent AMOC Program Publications

Baringer, M. O., T. O. Kanzow, C. S. Meinen, S. A. Cunningham, D. Rayner, W. E. Johns, H. L. Bryden, J. J-M. Hirschi, L. M. Beal, and J. Marotzke, The Meridional Overturning Circulation, in State of the Climate in 2009, D. S. Arndt, M. O. Baringer, and M. R. Johnson (eds.), Bull. Am. Met. Soc., 91(6), 66-69, 2010.

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APPENDIX 3. AMOC Program Annual PI Progress Reports

1. *Design and Implementation of an AMOC Observing System*

Western Boundary Time Series project

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The object of this program is to maintain the 25+ year time-series of the western boundary warm-upper limb and cold-deeper limb components of the MOC at 27°N in the Atlantic. Nearly continuous records of Florida Current transport and water mass properties have been made since 1982, while volume transport and water mass measurements of the Deep Western Boundary Current and the Antilles Current have been made since 1984. These measurements planned to be continued indefinitely.

Recent results include:
(1) A paper (Meinen et al., 2010) was published detailing time scales and structure of Florida Current transport variability during 1964 through 2007 using a variety of observing systems. It was shown that given the extremely energetic high frequency (sub-annual) variability observed in the Florida Current, only long-term continuous observations will allow for the evaluation of long-term trends or low frequency oscillations. From 1964 to the present there is no indication of a statistically significant trend in Florida Current transport, and interannual and longer time scale variations represent 10% or less of the total variance. Furthermore, while a plausible mechanism to explain the weak interannual variations has now been proposed and evaluated during the 1982-1998 period, the study of the longer record from 1964 to the present suggests that this mechanism is likely only one of several that can cause long-period variations in the Florida Current.
(2) A paper (Baringer et al. 2010) was published describing the state of the Meridional Overturning Circulation (MOC) for 2009 relative to a long-term climatology (with Meinen and many others). In this paper they show the variability of the MOC showing a large seasonal cycle, but no pronounced trend. The Florida Current, which also shows no strong trend, was shown to have a unique influence on east coast sea-level during several high water events.

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An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic

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The objective of this program is to establish an operational measurement system to continuously observe the strength and structure of the Atlantic meridional overturning circulation across the basin at 26.5º N. As of mid-2010 we had 5.5 years of data in hand from the full trans-basin array. With current funding the array will be maintained through 2014.

Recent results include:

(1) The mean MOC estimate remains stable at 18.7 Sv with r.m.s, variability of 4.9 Sv. The statistical uncertainty of the mean MOC estimate over the 4 years of observations is approximately +-2.1 Sv. (Kanzow et al., 2010).
(2) The associated meridional ocean heat transport is 1.33 +- 0.39 PW, with a statistical mean uncertainty of 0.14 PW. The meridional heat transport is highly correlated with the MOC strength, and the MOC carries 88% of the total heat transport. (Johns et al., in press).
(3) Both the MOC and the MHT have a significant annual cycle (+- 3Sv, +- 0.35 PW, respectively) that is associated primarily with changes in the interior ocean circulation driven by annual wind stress curl variability near the eastern boundary. ((Kanzow et al., 2010; Chidichimo et al., 2009).
(4) Damping of mesoscale eddy and wave variability near the western boundary of the oceans leads to considerably smaller stochastic MOC variability than would be predicted from open ocean eddy characteristics in the subtropics (Kanzow et al., 2009).

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Export Pathways from the Subpolar North Atlantic: Phase Two

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The objectives of this program are to provide an improved description of the spreading pathways of LSW in the western North Atlantic and their temporal variability based on the complete ExPath RAFOS float data set, to elucidate the relationship between LSW pathways and the strength of the deep recirculation east and south of the North Atlantic Current and Gulf Stream with a modeling study and an analysis of hydrographic and tracer data, and to document the extent to which LSW spreading pathways are linked to upstream conditions in the Labrador Sea using float, hydrographic and current meter observations as well as a modeling study.

Recent results include:

(1) RAFOS floats released across width of Deep Western Boundary Current (DWBC) at 50°N are not biased by release position to follow interior pathways. Detachment of LSW from the slope of the Grand Banks is a 2-d process, well captured by isobaric RAFOF floats. (Bower et al., 2010)

(2) Watermass (LSW) pathway variability can be traced to changes in the wind forcing of a basin. (Lozier and Stewart, 2008; Palter et al., 2008)

(3) Eddy-resolving general circulation model (FLAME) shows dominance of interior pathway, in contrast to non eddy-resolving circulation model (ORCA05) which does not resolve deep recirculations that provide alternate route for deep waters to enter the subtropics. (Gary et al., 2010; Bower et al., 2009; Lozier 2010)

(4) Mesoscale variability of the Gulf Stream around the Grand Banks has profound impact on LSW spreading pathways. (Bower et al., 2010, Gary et al., 2010)

(5) Overturning in the North Atlantic over the past fifty years is gyre-specific. (Lozier et al., 2010)

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

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Our research program seeks to document interannual transport changes in the DWBC and Gulf Stream and investigate their causes and consequences for the climate system. Our approach centers around sustained observations spanning the continental slope on a line running approximately from Woods Hole towards Bermuda involving moored instruments and repeated hydrographic section work: a study region we call 'Line W.' 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 2010 involved on-going analysis and write up of the Line W data obtained thus far, and a major cruise aboard *R/V Atlantis* (AT17) October 9-24 during which the moored array was serviced and the hydrographic section was reoccupied. The mooring and cruise data sets from the 2004-2008 time period have been finalized and submitted to the *OceanSites* data archive. Data have also been made available on our project web site: http://www.whoi.edu/science/PO/linew/index.htm.

Recent results include:

(1) For the 4-year period beginning spring 2004, we estimate the time-averaged top-to-bottom meridional transport of the waters shoreward of the Gulf Stream to be -36.2 ± 3.4 Sv, a bit less than Johns et al.'s reported - 40 ± 10 Sv but note that the uncertainty bounds of the two estimates overlap.
(2) Ph.D. student, Beatriz Pena, who successfully defended her dissertation in July 2010, discovered a notable shift in intermediate water PV that appears consistent with the time history of deep convection in the Labrador Sea and an advective time scale for those signals to reach Line W.
(3) On shorter time scales we have found that a significant amount of the monthly-timescale variability can be linked to local meanders of the Gulf Stream near the mooring array - with northward meanders corresponding to reduced DWBC the transport.

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Suppl., Abstract PO15C-07

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 at 16°N. The US portion of the system extends from the western boundary to the mid-Atlantic ridge, and in recent years IfM-GEOMAR has been operating a companion mooring near the Cape Verde Islands. As of December 2010 our timeseries is nearly 11 years long.

Recent results include:

(1) Careful data analysis of the fully-processed 9.5 year timeseries has shown a transport decrease in the southward North Atlantic Deep Water (NADW) by approximately 20% over this time period. This trend-fit is presently about 85% significant, and consistent in amplitude, vertical structure and timescale with prior oceanographic knowledge and model results. A new publication with these results has been prepared for submission to SCIENCE.
(2) In December 2010, two of the three MOVE moorings were recovered, and new moorings were deployed at all three sites. PIES (inverted echosounders with pressure sensors) data were retrieved at the section end points, and new PIES were deployed there for overlapping measurements. All new moorings and PIES have acoustic modems for data retrieval by ships or gliders now, and can remain deployed for at least 2 years. The inshore (on the slope) current meter mooring still needs to be recovered with a local vessel. NOAA could not provide sufficient ship time for all the MOVE work this year.
(3) Collaborations have been initiated with general circulation model (GCM) and coupled climate modelers from the US-AMOC community. Comparisons of the Estimating the Circulation of the Climate and Ocean (ECCO) model results (provided by Tong Lee at the Joint Propulsion Laboratory) with the MOVE transport observations will soon begin.

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South Atlantic MOC project ("SAM")

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This is a pilot program designed to measure the western boundary warm-upper limb and cold-deeper limb components of the MOC at 34.5°S in the Atlantic. This program began in 2009 and it is designed to be a first building block, coupled with a parallel French and South African effort on the eastern boundary, towards a future international trans-basin MOC observing array in the South Atlantic. The pilot western boundary array will also augment an existing program that estimates meridional volume and temperature transports using quarterly trans-basin expendable bathythermograph sections. Initial results suggest a high degree of deep transport variability on scales of weeks to months, although better evaluations of the variability time scales will be available when the records are longer.

Recent results include:

The SAM program is in its early stages and results are therefore coming mainly from connections to related programs. Recent results from these collaborations include:
(1) A paper (Perez et al., 2010) was submitted illustrating the results of a multi-model test of a variety of observing systems for the meridional overturning circulation in the South Atlantic. The results indicate improved performance for geostrophic-based measurement techniques at higher latitudes and, at 34.5°S, comparable performance in reproducing the ‘model truth’ for meridional overturning circulation and meridional heat transport with arrays involving realistic numbers of tall ‘dynamic height’ moorings or pressure-equipped inverted echo sounders.
(2) A related paper (Dong et al. 2009) was published indicating that at 34.5°S there is significant seasonal and longer time scale variability in the meridional overturning circulation in the basin interior as well as near the western and eastern boundaries, indicating the need to monitor all three regions in order to obtain accurate estimates for the meridional overturning circulation in the South Atlantic.
(3) Another related paper (Garzoli and Matano, 2010) analyzed the output of the POCM model and demonstrated that the South Atlantic is not a passive ocean for the AMOC compensating flows. Water mass transformations occur highlighting the need of observations in the region to better characterize the AMOC, while the importance of inter-ocean exchanges is shown to be key for signal attributions.

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Atlantic MOC Observing System Studies Using Adjoint Models

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

Recent results include:

(1) Discussions of observing systems have been provided by Heimbach et al. (2010a,b) and Wunsch (2010a).
(2) Estimates of the meridional overturning circulation are described by Wunsch and Heimbach (2009).
(3) Related work, primarily within the ECCO-GODAE project, has brought close to fruition a system with a full Arctic and far more accurate sea ice sub-model. That system (ECCO version 4) will be the platform for significantly extending the study of the Atlantic circulation.
(4) The meridional correlations of the meridional overturning circulation for the 16 years of ECCO state estimate v3.73 have been studied by Wunsch (2010b) and which imply subtropical variations are fundamentally uncorrelated with those in the subpolar gyre, at least over the time period of the estimate. The same paper produces estimates of the linear prediction times of the MOC and SST in the western subpolar gyre.

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Observing System Simulation Experiments for the Atlantic Meridional Overturning Circulation

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The long-term goals of this project are to (1) develop the necessary software to conduct Observing System Simulation Experiments (OSSEs) and Observing System Experiments (OSEs) as tools to design ocean observing strategies and (2) perform OSSEs and OSEs to design observational strategies for monitoring changes in the Atlantic Meridional Overturning Circulation (AMOC). The initial objectives of this project involved (1) building the hardware and software systems required to conduct OSSEs and OSEs at NOAA/AOML, UM/RSMAS, and UM/CIMAS, (2) evaluating the suitability of different ocean models for performing these experiments, and (3) estimating the errors in ocean variables produced by present-day numerical models required to optimally perform data assimilation experiments.

Recent results include:

(1) Calibration studies of the HYCOM data assimilation system using low-resolution Atlantic Ocean HYCOM runs and medium-resolution global HYCOM runs are being conducted. Initially the fixed-basis invariant of the Sequential Evolutive Extended Kalman (SEEK) filter is being used., Other assimilation methods will be implemented to assess the impact of assimilation methodology.
(2) The project is also performing initial OSE/OSSE tests in both the Atlantic and global domains that will focus on enhancements that have the potential to provide major improvements to monitoring the AMOC, e.g., (1) determine latitudes where cross-basin AMOC monitoring is particularly effective and (2) quantifying the improvement in AMOC representation achieved by extending ARGO float sampling below 2000 m into the deep ocean.

These initial experiments will not provide the final recommendations on observing system enhancements. Instead, this work represents a first step in the development of ocean OSSE capabilities for ocean climate studies. Development of such a system will occur over several stages where ocean models of increasing complexity and resolution (and hopefully increasing realism) plus more-advanced data assimilation techniques are used.

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Work to date has focused almost entirely on software development and testing. We are now preparing two papers, one on implementation of the SEEK filter in HYCOM and another on the initial OSE/OSSE tests with respect to designing observing strategies for the AMOC.

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

PIs: M. McPhaden[1], D. Zhang[1&2], W. Cheng[1&2], A. Biastoch[3]
Collaborators: R. Msadek[4], T. Delworth[4]

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The purpose of this program is to identify and investigate variables and processes that have been relatively well observed and can be associated with decadal-to-multidecadal changes of AMOC, and to examine these processes in GFDL climate model simulations.

Recent results include:

(1) The North Brazil Current (NBC) connects the North and South Atlantic, and is the major pathway for the surface return flow of the AMOC. The NBC geostrophic transport time-series is calculated based on 5 decades of observations near the western boundary off the coast of Brazil. Results reveal a multidecadal NBC variability that lags by a few years Labrador Sea deep convection. The NBC transport time series is coherent with the Atlantic Multidecadal Oscillation (AMO) in sea surface temperature that also has been widely linked to AMOC fluctuations. Our results thus suggest that the observed multidecadal NBC transport variability is a useful indicator for AMOC variations.
(2) The suggested connection between the NBC and AMOC is assessed in a 600-year control simulation of the GFDL CM2.1 coupled climate model. The model results are in agreement with observations and further demonstrate that the variability of NBC transport is a good index for tracking AMOC variations.
(3) Concerning the debate about whether a slowdown of AMOC has already occurred under global warming, the observed NBC transport time series suggests strong multidecadal variability but no significant trend.

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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 that operates on a weekly schedule between New Jersey and Bermuda. In addition to velocity, the Oleander Project includes a monthly XBT sections. The XBT program, operated by the National Marine Fisheries Service has been in continuous operation since 1977

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

Recent results include:

(1) Rossby et al. 2010 provides an updated overview of the longest time scales of variability in the Gulf Stream off the U.S. east coast using seventeen years of directly measured upper-ocean currents. Annually averaged transport variations suggest a correlation between the North Atlantic Oscillation (NAO) and both the Gulf Stream and the Sargasso Sea such that they both show a stronger component of flow to the west when the NAO is in a positive phase. These results, together with previous studies suggest that most of the observed variability in the GS itself can be accounted for in terms of time-varying winds over the North Atlantic. This would mean that the upper branch of the MOC, the other component of GS transport, has been quite stable over the last 80 years.
(2) The near-surface velocity and temperature spectra in the Gulf Stream region have comparable magnitude, in terms of the kinetic and potential energy, and both indicate a k^{-3} slope in the mesoscales. The k^{-3} slope, which appears to be in agreement with two-dimensional quasigeostrophic turbulence theory, does not support the contemporary surface quasigeostrophic theory. These results highlight large gaps in the current understanding of the nature of surface geostrophic turbulence.

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Analysis of eddies, mixing, and dense overflows at the Iceland-Faroe Ridge in the Northern Atlantic Ocean observed with Seagliders,

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This NSF-funded project represents the first use of autonomous gliders to study the dense overflows of the general ocean circulation. The preliminary scientific product is statistically reliable hydrography and velocity fields along the branch of the deep circulation at the southern flank of the Iceland Faroe Ridge. It is also the first use, to our knowledge, of vertical velocity measurements from a glider to shed light on deep-ocean mixing and internal waves.

Recent results include:

(1) Current work involves the vertical velocity field returned from deep Seaglider profiles. In Labrador Sea, the w-field shows distinct variation between deep winter convection sites and stratified, non-convecting regions, with greater energy in the deep mixing layers. The internal wave signature dominates stratified regions. At the Iceland-Faroe Ridge, in the path of the dense overflow waters, the w-field is being interpretted as a measure of turbulent mixing. At the Faroe-Bank Channel exit, this mixing converts the overflow water through entrainment, raising it to its eventual equilibrium depth (~ 2500m) where it settles as North Atlantic Deep Water. Comparison (graduate student N.L. Beaird) with free-fall turbulence probe observations of I. Fer in the same region has been encouraging.
(2) Water-mass transformation calculations with the Bergen Climate Model and CCSM3 provide a link between observations of in situ mixing and the parameterized mixing in global climate models (graduate student H. Langehaug). A key element in these models is the rapid entrainment of less-dense waters into the northern overflows, which occurs abruptly at the Greenland-Scotland Ridge. Ongoing exchange of students and PIs with University of Bergen has been a valuable component of this program.

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

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International Collaborators: Y. Gratton (INRS, CA), S. Dery (UNBC, CA)

The objective of this project is to quantify the variability in the freshwater outflow from Hudson Strait, the third largest oceanic contributor of freshwater to the North Atlantic, and to understand which processes regulate its variability. The project involves the analysis of moored data from the Strait, from 2005-2007 and 2008-2009, the use of a regional, high-resolution numerical model of the Hudson

Bay/Strait system and collaborations with hydrologists to quantify the river input into Hudson Bay (the primary fresh water source).

Recent results include:

Results to date show that the export of freshwater is highly variable and not correlated (on interannual timescales) with the river discharge into the bay. This discrepancy is attributed to the storage and release of freshwater from Hudson Bay as a result of variable wind forcing.

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Glacier-Ocean Coupling in a Large East Greenland Fjord

PIs: F. Straneo (WHOI),
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L. Stearns (KU)

The objective of this project is to investigate ice-sheet ocean interactions in one major glacial fjord, in southeast Greenland, and determine what oceanic processes control the rate of submarine melting and, hence, influence the stability of the outlet glacier.

Recent results include:

(1) The investigators have conducted repeated ship and helicopter based synoptic surveys of the fjord and nearby shelf area, used CTD tags on seals and, also, deployed moored instruments within the fjord. The measurements show that sub-surface subtropical waters (with temperatures at times above 4 °C) are present year round within the fjord and are rapidly replenished via wind-modulated exchanges with the shelf.

(2) Measurements in the vicinity of the glacier, furthermore, show that the Arctic and Atlantic water layering has a pronounced impact on the vertical distribution of submarine melting and, therefore, exerts an important constraint on glacier stability. These results indicated that changes in the upper warm branch of the MOC will be rapidly and directly communicated to the Greenland Ice Sheet margins where, in turn, they have the potential to affect glacier stability.

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Dynamics of Abyssal Mixing and Interior Transports Experiment (DynAMITE)

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DynAMITE is a process study to assess the strength of, and linkages between, the horizontal and vertical components of the AMOC that flow through the interior basin between 20-40° N. The field program is comprised of two elements: 1) an array of moored profilers designed to measure mass transports as a function of density along the southeastern flank of Bermuda Rise, a primary pathway for the interior circulation, and 2) a microstructure survey to obtain direct measurements of turbulent buoyancy fluxes across a range of topographic features. A particular objective is to characterize the structure of the diapycnal mixing field that contributes to abyssal water mass transformation and buoyancy gain in the interior basin, and to determine the strength of the lateral flows that result through planetary geostrophy and vorticity dynamics. More generally, it will quantify the strength of AMOC flows—from the UNADW down to AABW levels – that transit through the interior basin to join the DWBC near the RAPID array at 26.5°N.

Recent results include:

The 6-element moored array was installed down the southeast flank of Bermuda Rise in September 2010 and will remain in the water for a 1.5-year deployment period. Each mooring extends ~4000 m above the bottom and is instrumented with 2 McLane Moored Profilers (MMP) and fixed-point sensors (VACMs and Microcats) at the bottom, middle and top. The profilers are programmed to burst sample (4 profiles every 5 days) at ~6.2 hour intervals to minimize aliasing by tides, while the other sensors will acquire measurements at 15 min. intervals.

In spring 2011, a microstructure/CTD/bathymetry survey will be conducted between 20°N, the Mid Atlantic Ridge and Bermuda Rise using the High Resolution Profiler II (HRP-II). The program is in its early stages, and there are no results yet to report.

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 Meridonal Ocean Circulation (AMOC). Our project intends to address the following scientific questions: (1) what is the current state of the AMOC? (2) How has the AMOC varied in the past on the interannual to decadal or longer time scales? (3) Is the AMOC correlated with basin-scale sea level change?

Recent results include:

(1) Accuracy of the GRACE ocean bottom pressure data is primarily limited by land signal leakage and the knowledge of the glacial isostatic adjustment forward models. We developed a method to improve the mitigation of the Greenland ice melt signal contamination of the ocean, including the Labrador and Greenland seas (*Duan et al.*, 2009; *Guo & Shum*, 2009; *Guo et al.*, 2010).
(2) Sea-level rise budget and its contributions from Greenland ice-sheet fresh water freshening and steric sea-level have been assessed (*Shum & Kuo*, 2010, *Willis et al.*, 2010). Evidence of effect of abyss contributions of steric sea-level is being studied.
(3) We participated in *community white papers*, which contributed to the next decade's ocean and sea-level observations, *Ocean09*, and focused on the use of contemporary and future satellite data (*Cazenave et al.*, 2010, *Rintoul et al.*, 2010, *Shum et al.*, 2010).

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

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Collaborators: Tong Lee (JPL), Rong Zhang (GFDL), Timothy Liu(JPL) and Igor Yashayaev (Bedford Institute of Oceanography)

The first objective of this project is to determine what role, if any satellite remote sensing could play in the study of deep ocean convection, and specifically to identify the existence of the surface signatures, before and after the formation of deep convection. The second objective of this project is to analyze the influences of large scale changes to DOC in both time and space in the North Atlantic.

Recent results include:

(1) Different characteristic surface and subsurface features with and without DOC are examined. The weak (e.g., winter 2007) and strong DOC (e.g., winter 2008) events show (a) different strength of cyclonic flow fields along AR7-W, (b) small and large temperature differences at high latitudes from land surface temperature (LST) and sea surface temperature (SST), (c) southwest and northwest winds from wind field, respectively, and (d) strong land-air-sea interactions.
(2) Using long term temperature and salinity profiles collected from the basin, constant warming trends in the Labrador Sea of $0.6°C$ and $0.3°C$ in the upper and deeper layer respectively with slightly increase in the salinity of $0.02^{o}/_{oo}$ only in the deeper layer were observed for 2002-2009 period, which was found to be related to the variability of DOC. The consistence between the temperature and salinity variation from mid-1990s to present may indicate an ongoing decreasing strength of DOC in the Labrador Sea regardless of few strong convection interruptions.
(3) An algorithm to estimate subsurface thermal structure using bilinear regression method was developed. The long-term prediction showed that there are significant warming trends below the sea surface in the North Atlantic Ocean as well as in the Labrador Sea. The correlation and Root Mean Square Error (RMSE) between predicted and in situ observations were 0.92 and 0.56°C.
(4) The investigators developed an algorithm based on Ensemble Empirical Mode Decomposition (EEMD) to decompose altimetry data into different spatial scales. They identified that the modes 3 and 4 are associated with the Rossby waves in the North Atlantic Ocean, which were analyzed to examine the interactions between Gulf Stream variation and the Rossby waves.
(5) In order to estimate the contributions of different time scales to SLR, altimetry data was decomposed as seasonal, annual, interannual, decadal and inter-decadal time scales. The PIs found that annual and inter-decadal signals significantly contribute to SLR compared to seasonal and interannual signals. They also examined the influence of ENSO events to the SLR, showing that there

are close relations in low latitudes and eastern boundary on interannual time scales.

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

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Our objective is to explore satellite datasets to provide a baseline for future AMOC analyses, and to determine levels of variability associated with other causes, such as seasonal signals, dependences on the North Atlantic Oscillation, on the intensity of the Atlantic hurricane seasons, etc. Establishing reliable baselines, and variability, is a necessary first step to being able to identify “fingerprints” of changes in the strength of the AMOC in satellite data sets, especially those that will extend into the future.

Recent results include:

(1) A five-year time series of weekly SSTs over the Labrador Sea area from the V5 Pathfinder and the AVHRR on the NOAA Polar Orbiters has been analyzed to determine the length and severity of the winters that might be a diagnostic of deep-water formation. Two metrics were used: the length of the winter defined by a) the number of weeks for which the minimum SSTs were <-1^{o}C, and b) the time interval between the first and last incidences of minimum SSTs <-1^{o}C. The length of winter, as determined by the presence of SST<-1^{o}C is rather invariant from year to year averaging 25 weeks, with a range of 22 to 28 weeks, but the number of cold weeks does show interannual variability, ranging from 17 to 26 weeks.

(2) While the remotely sensed SST signals are indicative of possible interannual variations in surface heat flux that could indicate variability in surface-driven deep-water convection, the connection to signals of deep convection in the ARGO data in the Labrador Sea area is not straightforward. The seasonal heating and cooling cycle are clearly evident in the ARGO measurements in the upper 50-200m of the water column. The convincing signals of deep convection of cold water to >1000m are not apparent in the data analyzed thus far. Wintertime convection of water close to the freezing point reaches only about 500m, but where the water column sampled by the ARGO profilers as isothermal to

depths of ~1000m, the temperatures are not so cold. There is residual salinity-induced stratification indicating a limit to the depth of convection and the limited extent and occurrence of deep-water formation events. The results indicate that it is conceivable that the SST time series by themselves are inadequate predictors of deep-water formation. Wind fields from a range of sources will be incorporated into the analyses, as high winds during the winter months are also potential indicators of deepwater formation.

Monitoring the Atlantic Meridional Overturning Circulation using a combination of SST, altimeter, and Argo data

PI: J. Willis
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The objective of this project is to combine satellite observations with in situ temperature, salinity and velocity observations from the Argo array of profiling floats to estimate the Atlantic Meridional Overturning Circulation. It has been demonstrated that these global observing systems supplement moorings and ship based observing systems by providing an independent estimate of overturning and ocean heat transport time series at 41°N beginning in about 2002.

Willis (2010) found that overturning at 41°N varied seasonally but with significantly smaller amplitude than shown in the mooring data at 26.5°N. The mean transport was found to be 15.5 ± 2.4 Sv for the mean from 2004 through 2006. More recently, the heat transport has also been estimated using Argo and altimeter to be 0.52 ± 0.18 PW (Hobbs and Willis, in preparation). Time series of both heat and overturning volume transport will continue to be updated over the remaining two years of funding.

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2. *Assessment of the AMOC's role in global climate*

Impact of the Atlantic Meridional Overturning Circulation (AMOC) Variability on Arctic Surface Air Temperature and Sea-Ice Variability

PIs*:* Salil Mahajan (Oak Ridge National Lab, Oak Ridge, TN),
Rong Zhang, Tom Delworth (GFDL/NOAA, Princeton, NJ)

The objective of this project is studying of the impact of the AMOC variability on Arctic surface Air temperature (SAT) and sea-ice variability with the control simulation of GFDL CM2.1 climate model.

Recent results include:

The simulated AMO, which is mainly induced by AMOC variations, is robustly anti-correlated with the annual mean Arctic sea-ice extent anomalies and significantly correlated with the area averaged Arctic SAT anomalies on decadal timescales in the millennial simulation. The positive phase of the AMO is associated with a sea-ice decline in the Labrador, Greenland and Barents Seas. The recent declining trend in the satellite observed sea-ice extent also shows a similar pattern in the Atlantic sector of the Arctic, suggesting the possibility of a role of the AMO in the recent Arctic sea-ice decline in addition to anthropogenic greenhouse gas induced warming.

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

PIs: Y.-O. Kwon[1], C. Frankignoul[1,3], G. Danabasoglu[2]
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International Collaborators: G. Gastineau[3]
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The objective of this project is to understand the mechanisms of rapid transition between the different regimes of the Atlantic meridional overturning circulation (AMOC) decadal variability and assess its impact on the global climate using integrations with the NCAR Community Climate System Model version 3 and 4 (CCSM3 and CCSM4) in present day conditions.

Recent results include:

(1) The project has first focused on the differences between the two regimes of AMOC variability that are seen in CCSM3, i.e. a period with very regular and strong decadal (~20 yrs) variability and one with irregular and weak multi-decadal (~50 yrs) variability, in terms of the mechanisms and associated global climate impact. Close examination has been given to the latter weak multi- decadal regime, which lacks significant multi-decadal spectral peak in the atmospheric forcing represented by the North Atlantic Oscillation (NAO), unlike the previously documented strongly decadal regime (Danabasoglu 2008). The weak multi-decadal AMOC variability is found to be an ocean-only mode associated with the advection of density anomalies driven by stochastic atmosphere forcing around the subpolar gyre. The result also suggests that the slightly different strengths and extent of the subpolar gyre in the two regimes may be sufficient to result in two very different AMOC decadal variability regimes. The result has been submitted as a research article to a peer reviewed journal (Kwon and Frankignoul 2010). In addition, the result was presented at the “Second US AMOC Meeting” in Miami in June 2010.

(2) Recently, in collaboration with Dr. Gastineau at LOCEAN/IPSL the PIs have started to compare their CCSM3 result with the AMOC variability and associated climate impact from five different European climate models. Initial results indicate that the CCSM3 shows stronger contribution from the ocean circulation while the other models exhibit the variability primarily driven by the NAO.
(3) The project is beginning to examine AMOC variability from the newly released CCSM4 control integrations compared with CCSM3 runs. Unlike the CCSM3, different regimes of AMOC multi-decadal variability are not apparent in the CCSM4 simulations. However, the weakening trends of the amplitude of AMOC variability in time from the CCSM3 and CCSM4 are comparable.

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

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NOAA Project NA08OAR4320912

The objective of this project is to study the physical characteristics of SST variability related to the Atlantic Multidecadal Variability (AMV) in IPCC AR4 models, to evaluate the associated climatic impacts over land, to determine the link to the AMOC, and to assess AMV's predictability.

Recent results include:

(1) The published work emerging from this progress deals mainly with the impacts (mainly hydrological) of Atlantic multidecadal SST variability worldwide and the atmospheric mechanisms that are involved in bridging between the Atlantic Ocean and climate variability in the adjacent and remote land areas. Under this project the investigators concluded a study of the impact of Atlantic SST on US West rainfall and initiated work on the role of the AMV in variability of rainfall in southeast South America. The atmospheric bridge between the Atlantic and these regions is diagnosed as the Rosby wave response to changes in tropical Atlantic SST, which in turn appear linked with SST variations in the extratropics, particular in the subpolar gyre region. These results indicate the importance of the AMV – which is primarily driven by internal interactions – in the global climate system.

(2) A paper on the remote influences of AMV on global surface temperature and on precipitation in AR4 preindustrial, 20th, and 21st century integrations is in final stages of preparation. The results display an overall lack of sensitivity of the AMV to anthropogenic forcing.

(3) The work to study the ocean mechanisms of AMV and its link to AMOC is in progress. The PIs are

currently analyzing a 4000-year control (pre-industrial) of the GFDL CM2.1 applying LIM methodology to determine the oscillations in the ocean state and their predictability.

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Collaborative Research: Towards An Understanding Of The Role of The Atlantic Thermohaline and Wind-Driven Circulation In Tropical Atlantic Variability (TAV)

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The objective of this research project is to gain a comprehensive understanding of the dynamical processes that link the changes in high latitudes to those in the tropics. The focus of this proposal is on the oceanic linkage. In particular, we seek to explore how changes in the Atlantic Meridional Overturning Cell (MOC) can affect the pathways of the Sub-Tropical Cells (STCs), and how these changes in the STCs can affect the Sea Surface Temperatures (SSTs), and finally how these SST changes can affect the coupled climate variability in the tropical Atlantic. The investigation is conducted via a hierarchy of coupled climate models in conjunction with observational analysis.

Recent results include:

(1) The tropical Atlantic SST responds nonlinearly to changes in AMOC strength. A prominent equatorial warming occurs when the AMOC is weakened below a threshold value. This nonlinear behavior is attributed to an interaction between the AMOC and the wind driven subtropical cells. We hypothesize that this AMOC threshold behavior is critical to the abrupt climate changes within the tropical Atlantic sector during the past climate event, such as Younger Dryas (Wen et al. 2010a and b).
(2) A modeling investigation on the mechanisms of SST changes in the Caribbean Sea during the Younger Dryas sheds light on the interpretation of Caribbean paleo-temperature reconstructions. Despite the proximity of the core locations, some paleo records show surface warming, while others indicate surface cooling during the Younger Dryas. We suggest that this inconsistency in the paleo reconstructions is due to the competing physical processes that tend to give opposite sign of

temperature changes off the northern coast of the South America in response to the weakened AMOC (Wan et al. 2009a).
(3) During the period of reduced AMOC, paleo proxy records indicate a corresponding surface salinity increase over the entire tropical Atlantic. We present new modeling results that show the basin-wide paleo-salinity response is attributed to a combined effect of the southward migration of the Atlantic ITCZ associated with the Northern Hemisphere cooling and AMOC induced oceanic pathway changes (Wan et al. 2009b).
(4) The PIs show that notorious climate model biases in the eastern equatorial Atlantic have a major effect on sea-surface temperature (SST) response to a rapid change in the AMOC. By comparing identical water hosing experiments conducted with two different coupled general circulation models, oceanic mechanisms underlying the difference in models' SST response are dissected. The results show that the different SST response is plausibly attributed to systematic differences in the simulated tropical Atlantic Ocean circulation. Therefore, in order to accurately simulate past abrupt climate changes and project future changes, the bias in climate models must be reduced (Wan et al. 2010b).

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3. *AMOC Variability Mechanisms and Predictability*

A COLLABORATIVE INVESTIGATION OF THE MECHANISMS, PREDICTABILITY, AND CLIMATE IMPACTS OF DECADAL-SCALE AMOC VARIABILITY SIMULATED IN A HIERARCHY OF MODELS

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This is a collaborative study between NCAR, GFDL, and MIT to i) characterize modeled Atlantic Meridional Overturning Circulation (AMOC) variability and its past, present, and future climate impacts, ii) identify the mechanism(s) of AMOC variability in the NCAR, GFDL, and MIT coupled models, and iii) explore the extent to which the AMOC is predictable by experimenting with prototype predictability systems initialized by ocean state estimates. Our initial focus has been primarily the analysis of the new coupled simulations performed at GFDL and NCAR for the IPCC AR5 with respect to their AMOC behaviors. Any new findings and AMOC differences from the previous versions have been immediately communicated within the group. As indicated below, several specific collaborative studies are underway.

Recent results include:

(1) At NCAR, work has progressed simultaneously on each of the three themes identified above. First, AMOC variability and its climate impacts continue to be assessed in the full suite of Community Climate System Model version 4 (CCSM4) fully coupled integrations: the pre-industrial controls, an ensemble of 20th century runs, and ensembles of future scenario runs. In general CCSM4 shows much less overall AMOC variance than was found in CCSM3, with only weak spectral peaks exceeding red noise at timescales longer than 50 years (Danabasoglu et al. 2011). The reasons for these AMOC differences between CCSM3 and CCSM4 are being explored. AMOC variability and associated climate impacts have also been assessed in a suite of historical ocean state estimations designed to provide ocean initial conditions for 21st century prediction experiments (Yeager et al. 2011; Tribbia et al. 2011). In particular, a 1948-2007 ocean-ice hindcast forced with atmospheric state fields exhibits a large upward trend in AMOC strength between 1960 and 2000 along with an associated Atlantic Multidecadal Variability (AMV)-like surface temperature signature, which compares well with observations. This forced hindcast will be compared to ocean state estimates from 1998-2007 in which World Ocean Database observations are used to constrain our ocean model below the surface using the Data Assimilation Research Testbed (DART). Both methods of ocean state estimation generate good comparisons with RAPID observations of AMOC and meridional heat transport (MHT) at 26.5^{o}N. The AMOC fingerprints identified in these simulations are directly compared to the observed record. Jointly with GFDL and W. Johns, the PIs have compared a variety of CCSM4 and GFDL simulations (both coupled and uncoupled) to estimates of MHT at 26.5^{o}N from the RAPID mooring array. They find that model underestimation of MHT at this latitude is due to too weak geostrophic gyre transport because of biases in temperature structure along the western boundary (Msadek et al. 2011).

(2) Work on identifying the mechanisms of AMOC variability in CCSM4 has focused thus far on exploring the sensitivity of AMOC variability to model configuration and parameterizations. Yeager and Danabasoglu (2011) explain the damping effects of a Nordic Seas overflow parameterization on AMOC variance on decadal and longer timescales. To explore the robustness of this finding, GFDL has implemented this overflow parameterization in their model and sensitivity experiments are just now underway. One of the findings in this analysis is that the time series of AMOC maximum is not necessarily a good index for quantifying overall AMOC variability and associated spectral power. The PIs have also explored the sensitivity of AMOC variability to atmospheric resolution and found that, in contrast to a similar comparison done using CCSM3, lower atmospheric resolution results in greater AMOC variability in CCSM4.

(3) In collaboration with GFDL and J. Anderson (CISL/NCAR), NCAR has developed an ocean data assimilation capability based on DART to obtain ocean initial conditions for AMOC predictability studies in CCSM4. As mentioned above, the project is now running an ongoing ocean state estimation using

DART with 48 ocean ensemble members which has completed historical years 1998-2002. A suite of fully coupled decadal prediction runs has been integrated following the CMIP5 experimental protocol using ocean initial conditions obtained from this DART assimilation as well as from forced ocean-ice hindcasts. The AMOC evolution in initialized decadal prediction experiments differs significantly from that in uninitialized scenario runs, but useful predictive skill associated with this full-field ocean initialization method remains to be demonstrated. The PIs continue to analyze these prediction simulations to quantify the predictability of AMOC and its climatic fingerprints.

(4) At GFDL, two suites of prototype decadal hindcasts and predictions have been completed using the GFDL CM2.1 coupled model and the GFDL coupled reanalysis system. The two versions differ in some of the details of the coupled reanalysis. Each suite consisted of over 4000 model years. The predictive skill in the hindcasts is being investigated.

(5) In order to establish credibility of the decadal predictions, hindcasts must be run so that the prediction system may be validated. The temporal inhomogeneity of the ocean observing system makes the verification a challenge. Using the present-day observing system of ARGO and altimetry, basis functions for the global temperature and salinity relationship were constructed so that it is possible to go back to 1993 with XBT data and construct corresponding pseudo salinity profiles. This allowed for a better initialization and verification of the decadal hindcasts from 1993-2002 (Chang et al. 2010).

(6) The AMOC has an important influence on climate, and yet adequate observations of this circulation are lacking. A study was conducted at GFDL to assess the adequacy of past and present ocean observing systems for monitoring the AMOC and associated North Atlantic climate. This was accomplished by using a perfect model OSSE (Zhang et al. 2010). A perfect predictability study of the AMOC in GFDL CM2.1 was also completed and published (Msadek et al. 2010). This study probed characteristics of the predictability related to subsurface temperature and sea level height.

(7) A collaborative study is underway with colleagues at PMEL to investigate the connections of the North Brazil Current to the AMOC. This has implications for AMOC monitoring and mechanisms (Zhang et al. 2011).

(8) Another avenue pursued at GFDL is the development of a new high resolution model (GFDL CM2.5). This builds on the GFDL CM2.4 model by increasing the atmospheric resolution. Multi-century control and climate change simulations have been completed. Particular attention has been paid to the AMOC and its variability. The model shows significant multidecadal variability in the Greenland Sea, but only muted AMOC variability. This may be related to persistent biases in Labrador Sea convection (Delworth et al. 2011). The project continues to investigate the dependence of model variability and response to perturbations with both of our high resolution models (GFDL CM2.4 and GFDL CM2.5). One aspect of this work has shown that oceanic mesoscale eddies play an important role in the response of the Southern Ocean to wind stress changes (Farneti et al. 2010). GFDL is also developing CM2.6, a model with a 50 km atmosphere and a 4-10 km ocean.

(9) The MIT group has also been analyzing the AMOC variability in the NCAR and GFDL simulations discussed above as well as in the MIT coupled model to identify robust underlying mechanisms. The pacemaker appears to be set in the subpolar basin of the Atlantic: variability in the AMOC of the subtropical gyre to the south lags that of buoyancy anomalies in the subpolar gyre by the time it takes a signal to be advected in the deep western boundary current. Another focus at MIT has been the development of 'toy models' of AMOC variability inspired by mechanism explorations above, based on delayed oscillator models for the pacemaker region. Model parameters are fit to spectra of AMOC and

temperature variability in the coupled models and used to explore AMOC predictability horizons.

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Latitudinal Dependence of Natural Variations and Anthropogenically Forced Changes in the Atlantic Meridional Overturning Circulation (AMOC)

PI*:* Rong Zhang (GFDL/NOAA, Princeton, NJ)

This project is studying the meridional coherence of AMOC variations and the northward intensification of anthropogenically forced AMOC changes in density space

Recent results include:

(1) This study using the GFDL coupled climate model (CM2.1) shows that AMOC variations estimated in density space propagate with the advection speed from Flemish Cape to Cape Hatteras, resulting in

a several-year time lead between subpolar and subtropical AMOC variations and providing a more useful predictability. AMOC variations have significant meridional coherence in density space.
(2) In density space, the anthropogenically forced AMOC weakening over the 21st century is larger at northern high latitudes (about 50%; nearly twice of those at lower latitudes) due to changes in the North Atlantic deep water (NADW) formation. Anthropogenically forced AMOC changes are much smaller in depth space at the same northern high latitudes. Hence, projecting AMOC changes in depth space would significant underestimate AMOC changes associated with changes in NADW formation. The simulated AMOC weakening under anthropogenic forcing cannot be distinguished from that induced by natural AMOC variability for at least the first 20 years of the 21st century, although the signal can be detected over a much longer period.

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Predicting the Atlantic Meridional Overturning Circulation (AMOC) Variations Using Subsurface and Surface Fingerprints

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This project is developing a statistical predictive model of AMOC variability based on the observed subsurface temperature (Tsub) and SSH fingerprints of the AMOC

Recent results include:

(1) A statistical model is fit to the leading mode of objectively analyzed detrended North Atlantic Tsub anomalies (1955-2003) and is applied to assimilated Tsub and altimetry SSH anomalies to make predictions. The statistical model predicts a weakening of AMOC strength in a few years after its peak around 2005.
(2) A similar statistical model, fit to the timeseries of the leading mode of modeled Tsub anomalies from the GFDL CM2.1 control simulation, is applied to predict modeled Tsub, SSH, and AMOC anomalies. The two models show comparable skills in predicting observed Tsub and modeled Tsub, SSH, and AMOC variations.

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Pathways of Meridional Circulation in the Ocean Climate System

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This project aims to understand the warm branch of the meridional circulation of the Atlantic Ocean, particularly between the warm subtropics and the cold subpolar gyre. Our primary tools are satellite altimetry, diagnostic circulation/hydrography models, combined with in situ observations and climate/general circulation models. The present work builds on our successful identification of the dominant decadal variability of the northern Atlantic using NASA satellite altimetry (beginning with Hakkinen and Rhines, Science, 2004), which has stimulated much work of collaborators and others discovering the impacts of this long-term decline of the subpolar surface gyre on the hydrography and biology of the region.

Recent results include:

(1) Major progress during 2010 has been in combining altimetric surface height and the subsurface circulation as represented in the SODA ocean assimilation model of J.Carton, which extends analysis back to 1960. This has led to strong support for the hypothesis that the warming and salinity increase in the northern Atlantic during the past decade is through the opening of exchange pathways between subtropical and subpolar regions. Tracking tracers and particles while coordinating with surface eddy energy from satellite altimetry and the PIs' earlier surface drifter analysis, leads to a pattern of enhanced flow from the Gulf Stream directed northward to high latitude. This in turn connects with the gyre circulation which they have earlier identified as the principal variability of the upper north Atlantic during the satellite altimetry era.
(2) The primary atmospheric forcing relating to shifts in the warm AMOC branch involves both winds and air-sea buoyancy flux. New results suggest a particular role for atmospheric blocking patterns, above and beyond basic NAO statistics. The principal EOFs of the wind-stress curl combine to give a time-series that coincides with three periods of decadal warming of the subpolar zone: 1960s, early 1980s, late 1990s-2000s. In turn these cycles are prominent in longer reconstructions of Atlantic Meridional Variability.
(3) In collaboration with Eldevik and Langehaug of University of Bergen the PIs are analyzing water-mass transformation in the subpolar Atlantic/Nordic Seas using the Bergen Climate Model and NCAR's CCSM3. Connecting the variability of flow between subtropical and subpolar gyres involves Subpolar Mode Water transformation and mesoscale eddy processes which are parameterized in climate models.
(4) It is essential to connect the surface altimetry-based circulation field with the deeper circulation. The project is using the SODA assimilation model of J.Carton to do this, examining the vertical structure of velocity and hydrography to diagnose horizontal buoyancy advection, deep convective mixing and vertical velocity fields.

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Assessing Meridional Transports in the North Atlantic Ocean

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The goal of this study is to explain observed decadal anomalies of heat and freshwater in terms of the mechanisms that move water properties poleward. A primary candidate is the meridional excursions of the boundary between ocean gyres. Analyses of high-resolution ocean models and altimetry and related observations focus on property and property transport anomalies, excursions of the gyre boundary, and the role of wind forcing.

Recent results include:
(1) In an analysis of the contributions of several mechanisms to North Atlantic sea level variability, graduate student Jinting Zhang found that the topographic Sverdrup balance can reproduce qualitatively several distinctive features of the circulation.
(2) Two review articles on air-sea interaction in western boundary currents were completed as part of the USCLIVAR Western Boundary Current Working Group: a comparison of observations of the Gulf Stream and the Kuroshio Extension (Kelly et al 2010) and a large-scale review article on mechanisms (Kwon et al, 2010).
(3) An analysis of the heat budget in the Gulf Stream and the North Atlantic Current using four different modeling systems shows that upper ocean heat transport convergence drives the heat budget in both regions with surface heat flux a much smaller contributor on interannual time scales, confirming earlier results by Kelly and Dong (2004).
(4) An analysis of SST variability in the Kuroshio Extension in a coupled climate model and comparisons with satellite observations of SST and SSH was just accepted in J. Climate (Thompson and Kwon, 2010).

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Dynamics of the Atlantic meridional overturning circulation

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Historically, a hierarchy of ocean models has been used to investigate the dynamics of basin-scale, deep, meridional overturning circulations (MOCs). Near the base of this hierarchy are idealized solutions forced only by a surface buoyancy flux, Q.

As a first step of our Atlantic MOC project, we are exploring unresolved dynamical aspects of such base solutions. We use two types of models: a variable-density, layer ocean model (VLOM) and an ocean general circulation model (COCO), the former allowing for analytic solutions and the latter for more accurate representation of processes. Solutions are obtained in an idealized, flat-bottom basin extending from the equator to 60°N, and for simplicity density is assumed to depend only on temperature T. Our standard solutions are forced by a surface heat flux Q, which relaxes near-surface temperature to a prescribed $T^*(y)$ that decreases linearly in the latitude band 30−50°N from 23°C in the south to 3°C in the north.

When the models include advection and mixing, solutions necessarily adjust to a steady state with an MOC. One of the most important processes for generating the MOC is dynamical adjustment along the eastern and western boundaries. Initially, Q forces a shallow, thermally-driven, eastward flow across the basin from 30−50°N where $T^*_y \neq 0$. At the eastern boundary, the poleward propagation of Kelvin waves cancels this current by adjusting h_1 to a (nearly) parabolic profile $h_e(y)$ that thickens poleward (Sumata and Kubokawa, 2001) and reaches the ocean bottom just south of 50°N. In contrast, h_1 along the western boundary, h_w, remains thin, in large part because of the propagation direction of Kelvin waves is equatorward there. A consequence of the large difference between h_e and h_w is that there is a positive, zonal pressure gradient across that basin in layer 1, and it drives the northward-flowing, MOC surface branch. A paper describing this research is nearing completion.

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

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The main objectives of this proposal are to investigate the similarities and differences in the AMOC-related processes between observations and model simulations, and to diagnose the potential causes underlying the observed differences in the role of Ekman and geostrophic transports, as well as the overturning and horizontal transports to the AMOC and the net northward heat transport in the North and South Atlantic on seasonal to longer time scales.

Global ocean simulations at 0.72-degree resolution are now being run at AOML from 1948-2009 using two different configurations of HYCOM. These experiments will be used to investigate seasonal to interannual variability in the AMOC and assess the sensitivity of scientific results to model parametrizations and numerical algorithms.

Results from recent related studies:

(1) Dong et al. (2009) found that, different from numerical simulations, contributions of geostrophic and Ekman components to the AMOC are out-of-phas on seasonal time scale at 34.5°S. This study of the trans-basin XBT line also indicated that transport variability of all three regions (eastern and western boundaries, and ocean interior) is comparable, suggesting the importance to monitor all three regions in order to quantify changes in the AMOC.
(2) Examination of an eddy-resolving model outputs (Dong et al. 2010) also suggested that ocean interior region contributes significantly to long-term changes in the strength of the AMOC at 34°S, and the inter-ocean exchanges are important to explain the long-term changes in the northward heat transport.

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Studies of the influence of the Antarctic Circumpolar Current on the Atlantic meridional circulation

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

Recent results include:

(1) A suite of numerical simulations of AMOC in global and Atlantic-only configurations demonstrates the fundamental importance of the ACC stratification in controlling the AMOC strength. Direct influence of Ekman transport and eddy-driven heat/salt fluxes at the ACC-Atlantic boundary has a secondary importance (*Kamenkovich and Radko,* to be submitted).
(2) Numerical simulations of the AMOC response to a North Atlantic freshwater anomaly demonstrate that a delay in ACC response to such forcing acts to destabilize AMOC and amplify weakening of the AMOC strength (*Kamenkovich and Radko,* to be submitted).
(3) An analytical model of the Atlantic deep stratification and AMOC has been developed in order to illustrate the dynamics of the ACC-Atlantic coupling. The model predicts the stratification and meridional transport as a function of the mechanical and thermodynamic forcing at the sea-surface (*Radko and Kamenkovich,* in press). The analytical model demonstrates that the mean stratification of the lower thermocline is determined by the surface forcing in the ACC and, to a lesser extent, by the North Atlantic Deep Water formation rate; the overall effect of diapycnal mixing on the net stratification is surprisingly limited. The results suggest the interpretation of the ACC as an active lateral boundary layer that does not passively adjust to the prescribed large-scale solution, but, instead, forcefully controls the interior pattern (*Radko and Kamenkovich,* in press)
(4) An adiabatic component of the AMOC, as described using the "push-pull" formalism of *Radko et al.* (2008 in *JPO*; supported by this grant), and its response to intensifying atmospheric forcing (SRES A2 IPCC scenario) have been calculated from the outputs of GFDL CM2.1 and CCSM 3.0 model (*M. Han,* MS Thesis, in preparation). The isopycnal AMOC weakens in time in response to the buoyancy forcing in the North Atlantic; the decrease in the push-pull mode is weaker, which is explained by a delayed response of the Southern Ocean. Changes in the adiabatic push-pull mode are primarily caused by the anomalous surface heating in the high-latitude North Atlantic (*M. Han,* MS Thesis, in preparation).

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APPENDIX 4. SAMOC Draft Implementation Plan

South Atlantic Meridional Overturning Circulation – Future observing system

Background/Introduction

Observations and coupled climate models consistently indicate that variations in the Meridional Overturning Circulation (MOC) are strongly correlated to important climate changes such as variations in precipitation and surface air temperatures over large regions of the globe. To date, most MOC observations have been focused in the North Atlantic, however model studies show that the South Atlantic is not just a passive conduit for the passage of water masses formed in other regions of the world ocean but instead actively participates in their transformation. Water mass transformations occur across the entire basin, but are intensified in regions of high mesoscale variability, particularly at the Brazil/Malvinas Confluence and at the Agulhas Retroflection. Models and observations also show that the South Atlantic plays a significant role in the establishment of oceanic teleconnections. For example, model results indicate that anomalies generated in the Southern Ocean are transmitted through inter-ocean exchanges to the northern basins. The Agulhas leakage influence reaches the northern hemisphere and models suggest that changes occurring in the South Atlantic alter the global MOC. These results highlight the need for sustained observations in the South Atlantic and in the choke points in the Southern Ocean, which, in conjunction with modeling efforts, would improve understanding of the processes necessary to formulate long-term climate predictions. Further information and references can be obtained at

www.aoml.noaa.gov/phod/SAMOC.

The way forward

Based on the community discussion and agreement achieved during the three international South Atlantic Meridional Overturning Circulation (SAMOC, www.aoml.noaa.gov/phod/SAMOC/) workshops, an implementation plan is being prepared that will provide a plan for moving forward on measuring the strength of the MOC as well as the meridional heat transport and the meridional fresh-water transport in the South Atlantic, all of which are crucial to improving understanding of climate system variability. This document represents a preliminary executive summary of the forthcoming SAMOC implementation plan that will be provided to the US (and international) funding agencies for their review.

What needs to be measured?

To characterize the time-mean and time-varying components of the MOC in the South Atlantic, as well as the heat and salt carried by the MOC, it will be necessary to measure the full-water-column, full-basin-width, meridional velocity (along with temperature and salinity). Experience gained in the implementation of the North Atlantic MOC observing array at 26.5°N suggests that it is critically necessary to obtain MOC estimates at a very high sampling rate, i.e. daily, to avoid aliasing high-frequency fluctuations into the semi-annual, annual, and longer periods that are of significant interest to climate studies. Tests of prospective array types in a variety of ocean models suggest that 'geostrophic-style' mooring arrays, i.e. those which provide estimates of full-water-column density profiles, are likely to provide very accurate transport estimates for calculating the MOC, although care must be taken not to design an array so zonally sparse as to provide insufficient heat and salt information for calculating meridional transports of those quantities. In addition to a moored timeseries array, it will be important to collect trans-basin hydrographic sections for aid in the analysis and attribution of the moored observations.

<u>Where do measurements need to be collected?</u>

Numerical model studies completed in the United States, the United Kingdom, and in Brazil, as well as theoretical studies in the Netherlands, indicate that the higher latitudes (30°S to 34.5°S) are likely to produce more robust estimates of the MOC for several reasons. First and foremost, higher latitudes provide stronger density gradients, leading to improved signal-to-noise characteristics for geostrophic velocity calculations. Secondly, the strongest signals are more tightly confined to the boundaries at higher latitudes, particularly the eastern boundary, meaning the more intensely sampled array can be done in a smaller region. Thirdly, the measurement of the stability of the MOC, a crucial factor in attribution of observed signals, is more favorable at higher latitudes. Finally, several ocean model studies indicate that at higher latitudes it is possible to utilize less expensive mooring technologies (i.e. inverted echo sounders) more effectively in some locations, reducing the cost of the overall system. The community recommendation is that a SAMOC monitoring array be located between 30° and 34.5°S, and that it involves 10-20 deep ocean moorings, a combination of tall moorings and pressure-equipped inverted echo sounders, coupled with several shorter direct velocity moorings on the shelf on either side of the basin. Furthermore, attribution of the observed signals at 30-34.5°S will require concurrent observations from Drake Passage and in the passage between Africa and Antarctica. Therefore, maintaining and augmenting the existing arrays in those areas will be crucial for success.

<u>What resources are already in place?</u>

Some observation systems are already in place that can be used as building blocks for a trans-basin array, while other existing global *in situ* and satellite data sets will provide crucial information for analysis and attribution of the data from the recommended program. Pilot boundary current measurement systems are already in place on the western boundary (USA-NOAA, Argentina-SHN, Brazil-USP, Navy) and on the eastern boundary (France_Ifremer, South Africa-UCT) along 34.5°S. Trans-basin expendable bathythermograph sections are collected quarterly (USA-NOAA) along 34.5°S, with trans-basin conductivity-temperature-depth sections collected less frequently in the region of 25°S-34.5°S as well (USA-NOAA/NSF, United Kingdom, Brazil). A group of North and South American countries operating through the Intra-Americas-Institute for Climate Change Research (IAI) have a large shelf-monitoring program planned for the western boundary that would fit together nicely with the western end of the recommended trans-basin array (USA-WHOI, USA-OSU, Argentina-SHN). Several groups already collect additional hydrographic observations in the region that would be extremely valuable for analysis purposes (Argentina, Brazil, France, Germany, Russia, South Africa, the United Kingdom, the United States). The global observing system, particularly the ARGO float network, the global drifter array, and satellite observations of sea height, sea-surface temperature, sea-surface salinity (SMOS, and upcoming Aquarius), and surface wind will also be crucial for analysis and attribution of signals observed by the moored system.

<u>What international partners are interested in contributing to this expanded effort?</u>

Based on conversations at the three SAMOC workshops in 2007-2010 (see webpage listed above), representatives from several countries indicated a willingness to provide ship-time for maintaining the array, including Argentina (Naval Hydrographic Service), Brazil (Naval Hydrographic Service), Russia (Shirshov Institute of Oceanography), South Africa (Univ. of Cape Town), and possibly the United Kingdom (National Oceanography Centre, British Antarctic Survey) in addition to the United States (NSF, NOAA).

<u>What plans are being formulated to address these goals?</u>

The following institution/countries have expressed interest in proposing specific parts of the recommended observing system:

1. Trans-basin CTD section (UM/USA, SHN/Argentina, USP/Brazil, AOML/USA)
2. Mooring array along 34.5°S (AOML/USA, SIO/USA, UM/USA, IFREMER/France)
3. Mooring array to monitor the Brazil Current (USP/Brazil, NOC/UK)
4. CTD/CO_2 line along 30°S (NOAA/USA)
5. Maintaining present observation programs in Drake Passage (SIO/USA, URI/USA, NOC/UK, SIO/Russia, LOCEAN/France)
6. Maintaining and augmenting present observation programs in the passage South of Africa (IFREMER and U Brest/France, UCT/South Africa, AWI/Germany, SIO and AARI/Russia, IIM/Spain, AOML/USA)

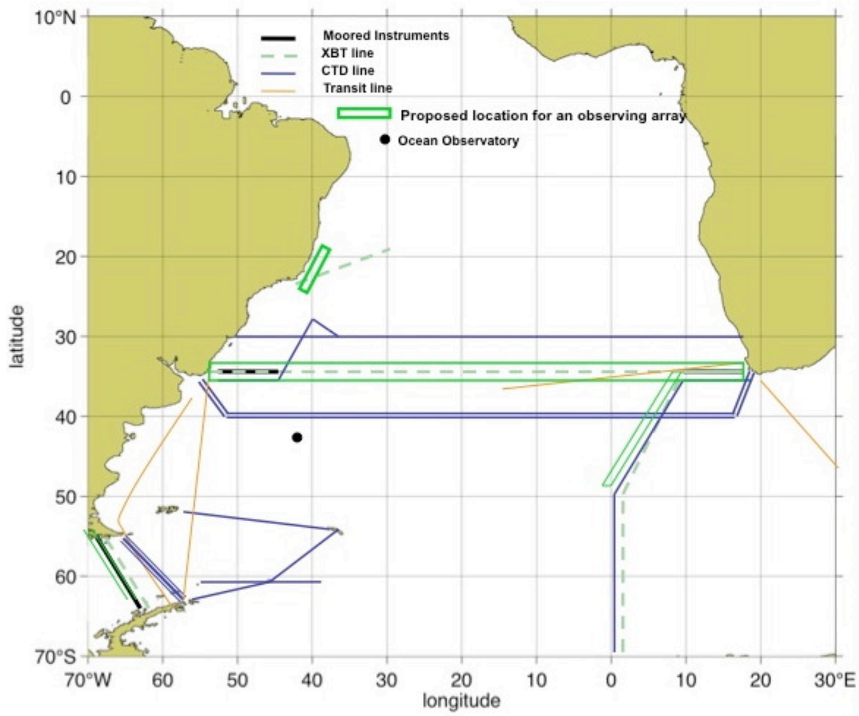

Figure 1. Existing observing system elements and proposed location for SAMOC observing line (produced by S. Garzoli, NOAA/AOML). For more information about the different existing and planned observing system elements included in this figure please see www.aoml.noaa.gov/phod/SAMOC/C&P_observations.html

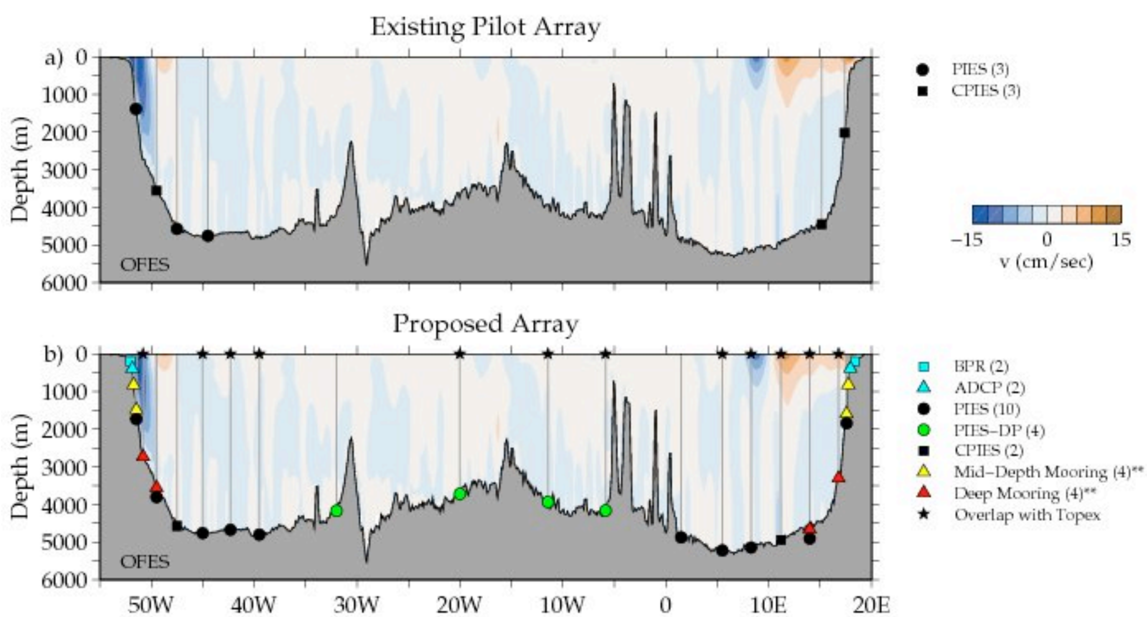

Figure 2. Existing pilot array, and preliminary design of SAMOC moored time series observing array along 34.5°S, superimposed on OfES model mean meridional velocity field (produced by R. Perez, NOAA/AOML & UM/CIMAS).