U.S. CLIVAR: Climate Variability and Predictability

Second Annual Progress Report for a JSOST Near-Term Priority

Assessing meridional Overturning Circulation Variability: Implications for Rapid Climate Change

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SECOND 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, that 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 second annual progress report submitted by the US AMOC Science Team. The goal of this report is to detail progress on the three main objectives of the program, identify gaps in its implementation, and make recommendations on how to fill those gaps.

Progress on the three main program objectives can be summarized as:

1. The design and implementation of an AMOC monitoring system

At present, AMOC monitoring in the U.S. is accomplished by a collection of field programs that were largely in place at the creation of the program. Several nationally and internationally-funded global-scale programs are presently returning data that contribute to AMOC monitoring but do not constitute an adequate monitoring system. These include Argo, JASON, the Global Drifter Array and the collection of satellites returning ocean surface and meteorological information. Several research efforts are presently utilizing these data to study and make proxy estimates of the time-varying AMOC, however, at present, the program's goal of providing "a continuous record of the zonally integrated, full-water column, trans-basin fluxes of heat, mass and fresh water carried in the AMOC" is yet unrealized.

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

Studies over the past year of global surface temperature have indicated that decadal-to-multidecadal temperature fluctuations contribute significantly to the warming of the past few decades and that the North Atlantic appears to dominate the global temperature fluctuations at decadal-to-multidecadal time scales. The latter finding suggests that the decadal-to-multidecadal temperature variation is attributable to

AMOC variations**.** Satellite altimetry observations and modeling analyses suggest a recent strengthening of the AMOC that may contribute significantly to the recent SST change. Furthermore, recent modeling results on the impact of the AMOC variability on the Arctic climate suggest that the intensifying AMOC, in addition to anthropogenic greenhouse gas induced global warming, might have contributed to the recent decline in the Arctic sea-ice, especially in the Labrador Sea and Nordic Sea. There is increasing evidence that changes in the upper, warm limb of the AMOC are impacting Greenland's outlet glaciers and affecting the ice sheet's mass balance. Finally, although a few climate model simulations suggest that the AMO is attributed to the AMOC variability, the physical mechanisms are not understood. An improved understanding of these mechanisms between the AMOC and AMO has an important implication for decadal climate predictions in the Atlantic sector.

3. An assessment of AMOC predictability

Assessments of what might potentially be predictable, to what degree, and via which physical mechanisms are currently under discussion in both the climate modeling and observing communities. 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 in the process of generating output useful for addressing AMOC predictability in the next few years.

While progress on program goals has been sustained to date, it has fallen short of the expectations set when the program was initiated in the spring of 2007. This shortfall is attributable to lower than anticipated funding levels for the program. To fill programmatic gaps we recommend that funding levels be brought to those originally envisoned for this program and that:

1. The design and implementation of a monitoring system for the time varying strength of the AMOC in the subpolar North Atlantic and subtropical South Atlantic be comprehensively planned this year and then realized in the next several years. It is crucial that resources be provided and coordinated internationally so that these quantities are well measured for a sufficiently long time to provide useful indices of various part of the AMOC system in their own right, and to provide the benchmarks needed to validate ocean state estimation models.

2. AMOC-induced climate signals be identified using existing observations and distinguished from anthropogenic climate change. Additionally, developing fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations should be supported. Finally, inter-model comparison and model-data comparison projects are required to gain better understanding of simulated AMOC oscillations and its relation to the SST variability in the models. Finally,

the linkage between the AMOC and AMO should be further explored.

3. Assimilation and non-assimilation modeling efforts be focused on reaching a consensus on the past variability of the AMOC and on advancing our nascent mechanistic understanding of the AMOC so that such models can be reliably used to guide the optimization of a long-term monitoring system. In particular, it is recommended that we assess our ability to detect AMOC-related climate variability and changes that occurred in the past few decades, for such climatically important quantities as transports and storage of heat and freshwater, air-sea fluxes, as well as SSH and SST patterns, and that we understand the uncertainties of existing estimates and the accuracies required to detect climatically important AMOC-related changes.
4. Studies that explicitly address the impacts of changes in the AMOC on climate-relevant variables such as sea ice, marine ecosystems, sea level, and carbon uptake be supported.

5. Assessments of the impact of existing or hypothetical observations on AMOC-related estimates be supported. Because no comprehensive measurement systems currently exist or are planned that are capable of providing broadscale measurements of the ocean below 2000m, direct assessments of the volumetric heat and freshwater content of the deep ocean makes it difficult to assess the AMOC's role in absorbing the excess heat caused by anthropogenic climate forcing. Thus, an examination of the potential impact of having full-depth measurements, either via ARGO floats or other platforms, should be encouraged.
6. In conjunction with the U.S. Climate Change Science Program (CCSP), a coordinated effort focus on the assessment of the potential predictability of the climate system on decadal time scales and the AMOC's role in that predictability.

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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 second 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 gaps in the programmatic needs.

B. PROGRESS ON PROGRAM OBJECTIVES

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

It was argued in the report "Implementation Strategy for a JSOST Near-Term Priority - Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change, October 24, 2007," that *"in order to assess the predictability of the AMOC, to determine its influence on climate, the carbon cycle, sea ice and related variables, a continuous record of the zonally integrated, full-water column, trans-basin fluxes of heat, mass and fresh water carried in the AMOC is paramount."* The report authors went on to recommend that "*the* [AMOC] *program emphasize the construction of one or more measurement systems to yield time series of the state of the AMOC.*" What might constitute such systems has not yet been defined. The report authors hold up the U.K.-U.S. activity at 26^{o}N (RAPID/RAPID_WATCH-MOCHA-Florida Straits see below) as a prototype, emphasizing a requirement that coast-to-coast observations are necessary. Additionally, local observations of individual elements of the AMOC can also provide valuable information about the Atlantic circulation and, in combination with other measurements and/or through assimilative modeling programs, will contribute useful information about net meridional fluxes. The U.S. AMOC program the design of an AMOC monitoring system is a work in progress.

a. *Currently in place*

i. National

At present, the U.S. AMOC monitoring "system" represents a collection of field programs, many of which were in place at the creation of the program. Several international, global-scale programs (with significant U.S. contribution) are presently returning data that contribute to AMOC monitoring (but not as stand-alone systems) including Argo, JASON, the Global Drifter Array and the collection of satellites returning ocean surface and meteorological information. Several research efforts are presently utilizing these data to study and make estimates of the time-varying AMOC including:

AMOC: Focused analysis of satellite data sets
PIs: Peter Minnett[1] and Chelle Gentemann[2]
[1] U. Miami, Miami, FL
[2]Remote Sensing Systems, Inc., Santa Rosa, CA

Evaluation of Meridional Transport of Water and Heat in the Atlantic Ocean Using Satellite Data
PI: W. Timothy Liu, Co-I: Xiaosu Xie
Jet Propulsion Laboratory, Pasadena, CA

Assessing Meridional Transports in the North Atlantic Ocean
U.S. PIs: K. A. Kelly[1] and L. Thompson[2]
[1]Applied Physics Lab, University of Washington , Seattle, WA
[2]School of Oceanography, U. Washington, Seattle, WA

Monitoring the Atlantic Meridional Overturning Circulation using a combination of SST, altimeter, and Argo data (AMOC, Altimetry and Argo)
PI: Josh K. Willis
Jet Propulsion Laboratory, Pasadena, CA

SODA: exploring centennial changes in ocean circulation
PIs: James Carton[1] and Benjamin Giese[2]
[1]Dept. Atmos. Ocean Sci., University of Maryland, College Park, MD
[2]Dept. Oceanography, Texas A&M University, College Station, TX

Pathways of meridional circulation in the North Atlantic Ocean
PIs : P.B. Rhines[1] and S. Häkkinen[2]
[1]University of Washington, Seattle, WA
[2]NASA Goddard Space Flight Center

As noted above, only 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:

Western Boundary Time Series (WBTS)
U.S. PIs: M. O. Baringer[1], C. S. Meinen[1], S. L. Garzoli[1]
[1]NOAA-Atlantic Oceanographic and Meteorological Laboratory
U.S. Collaborators: B. Johns[2], L. Beal[2] (MOCHA/NSF)
[2]RSMAS, University of Miami, Miami FL
International Collaborators: H. Bryden[3], S. Cunningham[3], T. Kanzow[3], J. Marotzke[4,]
J. Hirschi[3] (RAPID/NERC)
[3]National Oceanography Centre, Southampton, U.K.
[4]Max Planck Institut, Hamburg, Germany

An Observing System for Meridional Heat Transport Variability in the Subtropical Atlantic
U.S. PIs: B. Johns[1], M. Baringer[2], L. Beal[1], C. Meinen[2]
[1]RSMAS, University of Miami, Miami FL
[2]NOAA/AOML, Miami, FL
International Collaborators: H. Bryden[3], S. Cunningham[3], T. Kanzow[3], J. Marotzke[4] (RAPID/NERC)
[3]National Oceanography Centre, Southampton, U.K.
[4]Max Planck Institut, Hamburg, Germany
U.S. Collaborators: S. Garzoli[2] (WBTS/NOAA)

Another Atlantic basin-spanning observational program, but sampling the upper ocean only, involves expendable temperature probe deployments from ships of opportunity:

Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean.
U.S. PI's: M. O. Baringer[1], S. L. Garzoli[1], Gustavo Goni[1], Carlisle Thacker[1] and Claude Lumpkin [1] NOAA-Atlantic Oceanographic and Meteorological Laboratory
Related Project: Ship of Opportunity Program (SOOP): Volunteer Observing Ships:
Expendable Bathythermograph and Environmental Data Acquisition Program,
PIs M. O. Baringer[1], Gustavo Goni[1] and S. L. Garzoli[1]

Shifting focus to the south, the MOVE (Meridional Overturning Variability Experiment) program along 16°N has returned several years of net, full-depth meridional transport estimates between Guadalupe and the Mid-Atlantic Ridge. This project was initiated by researchers at IfM-GEOMAR and was largely transferred to SIO when Uwe Send relocated there. The MOVE array is currently fully operational, supported by NOAA/OCS. A new ocean time series station at the Cape Verde Islands (see below) extends the MOVE array to near full-basin width.

In the South Atlantic, a project led by researchers at NOAA's AOML has recently begun:

South Atlantic MOC (SAM)
U.S. PI's: C. S. Meinen[1], S. L. Garzoli[1], M. O. Baringer[1]
[1]NOAA-Atlantic Oceanographic and Meteorological Laboratory
International PI's: A. Piola[2], A. Troisi[2], E. Campos[3], M. Mata[4], S. Speich[5]
[2]Argentine Hydrographic Service (SNH)
[3]Univ. of Sao Paulo, Brazil
[4]FURG, Brazil
[5]LPO/IFREMER, France

This project involves an ongoing repeat high-density XBT line along 30°S that is soon to be supplemented with an array of C-PIES near the western boundary.

Additionally, while only indirectly related to the AMOC program, upper-ocean absolute velocity data across Drake Passage in the Southern Ocean are being regularly collected from Antarctic supply vessels by T. Chereskin (SIO) and E. Firing (SOEST). In addition, an array of CPIES across Drake Passage deployed in 2007 by T. Chereskin (SIO), K. Donohue (URI) and R. Watts (URI) will be recovered in 2011.

Shifting attention now to north of 26°N, 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 which operates on a weekly schedule between New Jersey and Bermuda. In addition to velocity, the Oleander Project includes monthly temperature measurements. The companion XBT program, operated by the National Marine Fisheries Service, has been in continuous operation since 1977.

The Oleander Project: Sustained observations of ocean currents in the NW Atlantic between New York and Bermuda

US PIs: K. Donohue[1], Charles Flagg[2] and H. Thomas Rossby[2]

[1]Graduate School of Oceanography, University of Rhode Island, Narragansett, RI
[2]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY

Moored and shipboard measurements are additionally being made along an altimeter-satellite ground track running southeast of New England towards Bermuda:

Line W: A sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39°N
U.S. PIs: J. Toole[1], R. Curry[1], T. Joyce[1], M. McCartney[1] and W. Smethie, Jr.[2]
[1]Woods Hole Oceanographic Institution, Woods Hole, MA 02543
[2]Lamont Doherty Earth Observatory, Palisades, NY 10964
International PI's: J. Smith[3]

[3]Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4T3 Canada
As will be noted below, Line W has ties to elements of the U.K. RAPID/RAPID_WATCH program. It also relates to a process experiment that utilizes acoustically-tracked floats to explore the connectivity between the subpolar and subtropical gyres:

Export Pathways from the Subpolar North Atlantic: Phase Two

PIs: Susan Lozier[1] and Amy Bower[2]
[1]Earth and Ocean Sciences, Duke University, Durham, NC
[2]Dept. of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA

At subpolar latitudes, a new addition to the AMOC assemblage of research programs is using remote sensing data to investigate deep convection in the Labrador Sea:

Satellite Multi-Sensor Studies of Deep Ocean Convection in Labrador Sea

PIs: Xiao-Hai Yan and Young-Heon Jo
Center for Remote Sensing, University of Delaware

In addition, several U.S. - led, international efforts are underway to quantify the exchange (of freshwater, in particular) between the subpolar North Atlantic and the Arctic region. These include measuring the flow through Davis Strait:

An Observational Array for High-Resolution, Year-Round Measurements of Volume, Freshwater and Ice Flux Variability in Davis Strait

PIs: Craig M. Lee[1], Dick Moritz[2], and Jason Gobat[1]
[1]APL, University of Washington
[2]Polar Science Center, University of Washington
International PI's: Brian Petrie[3]
[3]Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4T3

Canada and through Hudson Strait:

From rivers to the ocean: the dynamics of freshwater export from Hudson Strait

PIs: Fiamma Straneo[1], Steve Lentz[1]
[1] Woods Hole Oceanographic Institution, MA, USA
International PIs: Yves Gratton[2], Michel Harvey[3]
[2] University of Quebec, Quebec, CA
[3] Institute Maurice-La Montaigne, DFO, Quebec, CA

Efforts are also underway to quantify and monitor the inflow of warm, salty water of subtropical origin (carried by the upper limb of the AMOC) into several glacial fjords in East Greenland and its impact on the Greenland’s Ice Sheet outlet glaciers:

Glacier-Ocean Coupling in a Large East Greenland Glacial Fjord

PIs: Gordon Hamilton[1], Fiamma Straneo[2], David Sutherland[3], Leigh Stearns[4]
[1] University of Maine, ME, USA
[2] Woods Hole Oceanographic Institution, MA, USA
[3] University of Washington, WA, USA
[4] University of Kansas, KS

Additionally, repeat shipboard ADCP measurements have begun to monitor the northward flow of the warm North Atlantic waters through the Faroes-Shetland Channel and over the Faroes-Iceland ridge into the Greenland and Norwegian Seas. The MV Norröna is a large, high-speed ferry, based in Torshavn on the Faroes Islands and operated by the Faroese company, Smyril Lines p/f. that makes weekly runs between Denmark and Iceland.

The Norrona Project

US PIs: Charles Flagg[1] and H. Thomas Rossby[2]
[1]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY
[2]Graduate School of Oceanography, University of Rhode Island, Narragansett, RI

Beyond these sustained, *in situ* measurement programs, the CLIVAR-Carbon repeat hydrography program is planned to continue. Relevant to AMOC, re-occupations of lines along ~30S, 24N, 53W, near to along the Greenwich meridian, across Drake Passage, between Spain and Greenland and across the Labrador Sea are planned within the next 4-5 years.

ii. International

There are several research programs conducted by European investigators (in addition to Argo, the Surface Drifter program and satellite missions) that are either directly associated with AMOC projects or contribute indirectly. Chief among these is the U.K. RAPID/RAPID_WATCH program mentioned earlier. Three RAPID sub-programs bear directly on the U.S. AMOC measurement effort:

Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N

J. Marotzke[1], S. Cunningham[2] and H. Bryden[2]
[1]MPI, Hamburg, DE
[2]NOC, Southampton, UK

Cape Farewell and Eirik Ridge: Interannual to Millennial Thermohaline Circulation Variability

S. Bacon[1], E. Rohling[1] and D. Stow[1]
[1]NOC, Southampton, UK

A monitoring array along the western margin of the Atlantic

Chris Hughes[1], David Marshall[2], and, Richard Williams[3]
[1]Proudman Oceanographic Laboratory, UK
[2]University of Reading, UK, [3]University of Liverpool, UK

The first of these is linked to the U.S. projects along 26°N noted earlier, while the third has ties to the Line W activity, as well as to a Canadian program (AZMP) of short repeated hydrographic sections extending out from the Canadian Maritime provinces. The Cape Farewell project involves a moored array sampling the overflow water boundary current just south of Greenland.

Researchers at the IfM-GEOMAR lab in Kiel have been maintaining a moored array sampling the dense water boundary current export from the Labrador Sea near 53°N since 1997. At present, they hope to sustain this array through 2014 (paralleling the planned duration of the western boundary current sampling efforts at 39° and 26°N. The long-term Kiel group moored array program off Grand Banks (following an earlier 2-year-duration Canadian array) has ended, but new measurements in this region have been initiated and additional field programs are being planned. Specifically, M. Rhine reports that a moored array has been recently deployed in the western boundary current, with a final decision on her proposed transbasin array of PIES instruments to come in October. A separate proposal from P. Fratantoni and M. McCartney for western boundary current measurements was not accepted in 2009, but they are considering revision/resubmission.

Through the ASOF program and its continuation, European researchers have been observing the dense waters entering the Atlantic from the Arctic and the Greenland-Iceland-Norwegian (GIN) Seas. Specific projects include moorings near Denmark Strait from 1999 to the present (IFM-GEOMAR in collaboration with the Iceland Marine Research Institute, Macrander et al., 2005), in the Faroe Bank Channel since 1995 (Bjerknes Center in collaboration with Faroes Fisheries Laboratory; Hansen et al., 2001) and measurements of the flux through Fram Strait since 1997 (Norwegian Polar Institute; http://oceanography.npolar.no/oceanography/research/framstrait_fw.html). An effort has also been maintained to monitor the flow of warm Atlantic waters into the GIN seas (http://www.bodc.ac.uk/projects/european/maia/).

In addition, under a multi-institutional program called “Animate,” (Atlantic Network of Interdisciplinary Moorings and Time-series for Europe), several long-term ocean time series sites are being maintained. Four sites are presently indicated on the Animate web site (http://www.noc.soton.ac.uk/animate/): the Central Irminger Sea, the Porcupine Abyssal Plain, off the Canary Islands and newly initiated, off the Cape Verdes Islands. Chief focus on Animate is biogeochemistry, but these stations can also provide useful physical oceanographic observations. Reading from the web site, it seems that this program has suffered several mooring failures in recent years; thus the efficacy of Animate is unclear. And of course the very long records in the Norwegian Sea (Hydrostation M) and off Bermuda (Hydrostation S and BATS) are continuing, as is the annual reoccupation of the AR7W hydrographic section across the Labrador Sea by Canadian investigators. There is no funded effort in Germany at present to reoccupy the subpolar transocean section they sampled for several years during WOCE and ACCE.

b. *Gaps*

While each of the activities described above is focused on identifiable goals of the US AMOC program, collectively they are clearly insufficient to constitute an AMOC observing “system”. Furthermore, there is no such system in place nor are there currently any international plans for such a system.

While various observational programs that contribute to a study of AMOC continue, modeling efforts that focus on melding these observations into a coherent whole are underway. Funded U.S. AMOC projects in this area are:

Observing system simulation experiments for the Atlantic meridional overturning circulation
PI: George Halliwell[1], and W. Carlisle Thacker[2]
[1]U Miami, Mimai, FL
[2]NOAA/AOML, Miami, FL

AMOC observing system studies using adjoint models
P.I.: Carl Wunsch[1],Patrick Heimbach[1] and Rui Ponte[2]
[1]MIT, Cambridge, MA
[2]AER, Inc., Lexington, MA

Variability and Forcing Mechanisms of the Atlantic Meridional Overturning Circulation
P.I.: Tong Lee[1] and Geoffrey Gebbie[2]
[1]Jet Propulsion Laboratory, Pasadena, CA
[2]Harvard U., Cambridge, MA

A central goal of the latter project is to evaluate the consistency and fidelity of AMOC estimates from various state estimation products and identify the observational accuracy of AMOC that is required to distinguish the quality of different state estimation products.

Several other efforts are underway at the national (e.g., GFDL) and international level to use state estimation models to determine the time-varying AMOC strength. These efforts are presently coordinated through the CLIVAR Global Synthesis and Observations Panel (http://www.clivar.org/organization/gsop/reference.php). Ultimately these models should provide the best estimates of the large-scale ocean circulation and associated AMOC variability. However, at present there is considerable disagreement among models and substantial research is needed to further refine and validate them. An important near-term goal of US AMOC and related international programs should be to provide a set of high-quality observational benchmarks of AMOC variability that can be used to validate these models.

Key observational priorities in such a system should include:

- The Nordic Sea overflows
- Production and export of dense waters from the Labrador Sea
- The time varying strength of the AMOC in the subpolar North Atlantic following vertical entrainment and mixing processes
- The time varying strength of the AMOC in the subtropical North Atlantic (e.g., RAPID).
- The time varying strength of the AMOC in the subtropical South Atlantic.

Each of these priorities are currently being addressed at some level, but it is crucial that resources be provided and coordinated internationally so that these quantities are well measured for a sufficiently long time to provide useful indices of various part of the AMOC system in their own right, and to provide the benchmarks needed to validate ocean state estimation models.

A first vital step in this process is to conduct, with our international partners, an objective assessment of how effective existing observational efforts are in achieving these objectives, what resources might be added to enhance the accuracy and/or comprehensiveness of existing measurement systems, and to develop plans for continuous maintenance of these observations.

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

a. *Currently in place*

Although the AMOC has been invoked to explain past abrupt climate change, a mechanistic understanding of its role in the global climate has not yet been elucidated. Specifically, changes in the AMOC have not yet been conclusively determined to cause observed SST changes, which are known to drive climate variability. Therefore, an important objective of this program is 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 resultant climate variability. To meet this program objective, research must be conducted to develop an improved understanding of the physical mechanisms responsible for the AMOC and its variability, its relative importance for causing observed changes in Atlantic SST, and the impact of these changes on the large-scale climate over a variety of time scales.

At the last US AMOC Annual Meeting, participants identified a focused research area in the relationship between the AMOC and Atlantic Multidecadal Oscillation (AMO). The latter has received considerable attention because of its apparent linkage to a number of key climate phenomena over the Atlantic sector. Sahelian rainfall, for example, appears to be correlated with the multidecadal sea surface temperature (SST) variations in the Atlantic basin (Folland et al., 1986). Atlantic hurricane activity also appears to be influenced by the AMO (Landsea et al., 1999). Summer climate conditions over much North America and Europe may be modulated by the multidecadal sea-surface temperature (SST) variation associated with the AMO (Sutton and Hodson, 2005). Recent studies of global surface temperature indicate that decadal-to-multidecadal temperature fluctuations contribute significantly to the warming of the past few decades and the North Atlantic Ocean appears to dominate the global temperature fluctuations at decadal-to-multidecadal timescales (Huang et al, 2009 and Thompson et al. 2009). The latter has prompted the notion that the decadal-to-multidecadal temperature variation is attributed to variations in the AMOC. Satellite altimetry observation and modeling analyses suggest a strengthening of the AMOC in the recent decades that may contribute significantly to the recent SST change (Zhang, 2008). Although a few climate model simulations suggest that the AMO is attributed to the AMOC variability (e.g. Knight et al. 2005), the physical mechanisms are not understood. An improved understanding of these mechanisms between the AMOC and AMO has an important implication for decadal climate predictions in the Atlantic sector.

Furthermore, investigations into the impact of AMOC changes on sea ice, marine ecosystems, sea level and carbon and freshwater distributions are needed to more fully understand its climatic importance. Recent observational analyses show a rapid decline of Arctic sea-ice extent and thickness, and a rapid warming in Arctic surface air temperatures (SAT) (Deser and Teng, 2008) in recent years, confirming the amplification of SAT anomalies over the Arctic region (e.g. Chylek et al., 2009) suggested by modeling studies (e.g. Manabe and Stouffer, 1993). Whether the recent rapid warming over the Arctic is caused by enhanced anthropogenic greenhouse gas directly (e.g. Zhang and Walsh, 2006) or is amplified by oceanic low frequency variability, is still a matter of debate (e.g. Polyakov et al., 2003, Chylek et al. 2009). Recent modeling results on the impact of the AMOC variability on the Arctic climate suggest that the intensifying AMOC, in addition to anthropogenic greenhouse gas induced global warming, might have contributed to the recent decline in the Arctic sea-ice, especially in the Labrador Sea and Nordic Sea (Mahajan et al. 2009). One potentially very important and previously overlooked impact of the AMOC and its variability on global climate involves the Greenland Ice Sheet. There is increasing evidence that changes in the upper, warm limb of the AMOC are impacting Greenland's outlet glaciers and affecting the ice sheet's mass balance. Efforts are underway in south-east Greenland to monitor the inflow of warm waters inside several glacial fjords and investigate ocean/glacier coupling (Straneo).

Although overall progress on this program objective remains in its initial stages, several modeling efforts are now underway. The NOPP Program has chosen three AMOC related modeling projects: a study of optimal observing systems (Halliwell and Thacker), an analysis of ocean state estimates for AMOC from US and European assimilation projects (Lee and Gebbie) and an analysis of MIT-ECCO-GODAE results to design observing systems and understand the sensitivity of AMOC estimates to observing systems (Wunsch and Ponte).

Other efforts, not directly focused on AMOC, but nevertheless with important implications for the AMOC program objectives include the GFDL coupled modeling effort, which has broad climate research objectives, but also addresses many of the AMOC program modeling objectives by developing and analyzing coupled atmosphere-ocean-ice-land models to identify and elucidate the physical and dynamical mechanisms that maintain climate and cause its variations on seasonal to centennial time scales. The NCAR coupled climate modeling group also shares similar goals and interests. Both of these institutions are key US participants in the IPCC project. Internationally, several coupled modeling efforts are ongoing in Europe. Hadley, MPI and KNMI have a focus on the AMOC variability in the broad sense, often as a result of their participation in the IPCC project. MPI has an internal Millenium (coupled) modeling project (coordinator Jungclaus) to discriminate between internal variability, natural external forcing (orbital, solar, volcanic), and the anthropogenic-induced land-use-change and greenhouse-gas forcing. EU project DAMOCLES (Gasgard) focuses on the northern end of AMOC.

As listed in section B.1.a, efforts to reconstruct AMOC variability using data from existing global observing systems are ongoing. These include studies that focus on satellite data such as those of Minett and Gentemann; Liu and Xie; Rhines and Hakkinen; and Kelly and Thompson as well as an effort by Willis to combine Argo and altimetry data and a data assimilation effort by Carton and Giese. Some of the newly available satellite products include the water vapor transport integrated over the depth of the atmosphere and its divergence (equal to surface fresh water flux) at monthly, 0.5 degree resolution over the past decade (Timothy Liu). From these data the time mean meridional water flux could be computed as a function of latitude. Combined with the mass change from GRACE in the past 5 years, the time variable meridional fresh water flux could be determined. Ten years of stress (momentum flux) from the scatterometer is also available to calculate the Ekman transport. A recent study by Zhang (2008) demonstrates that the ongoing satellite and subsurface temperature measurements can be used to monitor future AMOC variations. An interesting recent work by Zhang and McPhaden (2009) shows promising results of a multi-decadal AMOC index reconstruction. Efforts to estimate and examine changes in the connectivity of transports and the storage of heat and freshwater using these data, either alone or with a model, must continue to be encouraged. The reconstruction effort should also include paleo proxy data.

b. *Gaps*

Despite the efforts listed above, substantial work remains to adequately assess the AMOC's role in the global climate system. Most of the gaps identified by the Implementation Strategy remain and little progress has been made to close them over the past year. In addition to the gaps discussed in the Implementation Strategy, no comprehensive measurement systems currently exist or are planned that are capable of providing broadscale measurements of the ocean below 2000 m, thus preventing direct assessments of the volumetric heat and freshwater content of the deep ocean. This gap makes it difficult to assess the AMOC's role in absorbing the excess heat caused by anthropogenic climate forcing.

As mentioned earlier, the gap in the understanding the linkage between the AMOC and AMO deserves special attention and should be considered as high priority research areas in the study of AMOC's role in the global climate. In particular, there is a need to identify AMOC-induced climate signal using existing observations and distinguishing it from anthropogenic climate change. Additionally, developing fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations is becoming paramount. Finally, inter-model comparison and model-data comparison projects are required to gain better understanding of simulated AMOC oscillations and its relation to the SST variability in the models. These efforts should be coordinated with the modeling centers.

In summary, further assimilation and non-assimilation modeling efforts are needed to reach a consensus on the past state of the AMOC and the relative importance of surface forcing in driving the observed AMOC variability. In addition, further analysis of available paleoclimate proxy data is needed in order to identify "fingerprints" of AMOC variability and to guide the collection of new proxy data. Studies are needed that explicitly address the impacts of changes in the AMOC on climate-relevant variables such as sea ice, marine ecosystems, sea level, and carbon uptake. Finally, additional analysis of observations and forcing fields along with ocean modeling efforts are needed to better establish the link between AMOC variability and SST changes that impact the climate system.

3. ***An assessment of AMOC predictability***

a. Research findings

Progress has been made in several areas related to AMOC decadal predictability:

Analyses of oceanic reanalysis data sets have demonstrated long response times that have implications for predictability. Hakkinen and Rhines (2009, and manuscript in preparation) have examined observed shifts in the North Atlantic Current paths and their relationship to the AMOC. Enhanced intrusions of highly saline subtropical waters have occurred with the NAO in a neutral or negative phase. The AMOC upper limb changes appear to be wind driven and associated with a weakened subtropical and subpolar gyre circulation. This particular oceanic response to the weak NAO persists for several years (5-10 years) influencing strongly the northern marine ecosystems and fisheries. The long persistence of the oceanic response allows some predictability for the upper ocean changes.

In work that is more explicitly related to predictions, a model-based assessment has been conducted on the influence of varying observing systems on the ability to represent and predict the AMOC. A recent study (Zhang et al, submitted) evaluated the effectiveness of various large-scale observing systems in representing the AMOC by assimilating synthetic observations as sampled from a climate model using varying observing systems. They then assessed how well various observing systems, in concert with a novel coupled assimilation system developed at GFDL, were able to recover the AMOC. They found that the ARGO network is a crucial component of the observing network, and allows a more accurate representation of the AMOC compared to earlier large-scale observing systems. The ARGO network provides measurements of temperature and salinity down to 2000 meters, thereby providing a more accurate representation of the density field. Prior to the advent of ARGO in the early 21st century, most observations were only for temperature in the upper several hundred meters, thereby providing a much weaker constraint on observed density changes. Within a perfect model framework, Zhang et al demonstrate that observing systems prior to ARGO have a significantly degraded ability to represent the AMOC.

In related work, Zhang and colleagues at GFDL are investigating the impact of observing systems on the ability to predict AMOC variability. Using a perfect model framework, preliminary results suggest that the addition of the ARGO network improves the ability of models to predict AMOC fluctuations. By providing a better initial condition through the incorporation of temperature and salinity to 2000 meters depth, the model has greater skill in predicting simulated AMOC decadal fluctuations.

Danabasoglu and colleagues at NCAR have been working with versions of the new Community Climate System Model version 4 (CCSM4) to characterize the decadal variability and predictability of the AMOC. They have analyzed a suite of integrations using atmospheric models of differing resolution and physics. They have also analyzed AMOC variability in models that include or exclude a new parameterization of overflows in the North Atlantic, particularly the overflows between the Nordic Seas and the North Atlantic. They find that in all of the model versions, the AMOC has a dominant EOF (accounting for more than 50% of the variance) associated with an overall strengthening/weakening of the North Atlantic Deep Water cell. However, the amplitude and temporal characteristics of the AMOC variability depend on the model formulation. Preliminary results show that the models without an overflow parameterization have more oscillatory AMOC variability than models that use this new parameterization. Further, in the experiments that were analyzed the average AMOC strength and variability appears to increase with atmospheric resolution. Additional work is underway to investigate decadal scale predictability of the AMOC in CCSM4 including through the use of the Data Assimilation Research Testbed (DART) for ocean initialization, and through hindcast experiments over the period 1948-2006 using Coordinated Ocean-ice Reference Experiments (CORE-II) forcing.

Work at the University of Miami and Texas A&M has investigated the influence of atmospheric weather noise on the mean AMOC state and its variability. Chang and Kirtman use an Interactive Ensemble (IE) technique (Kirtman et al., 2009), in which an ocean model can be coupled to the ensemble mean of multiple realizations of an atmospheric model. In taking the ensemble mean across the atmospheric model realizations, the weather noise is greatly reduced in amplitude. Fluxes going into the ocean therefore have reduced variance associated with the ensemble mean. Differences in model behavior between a coupled model with and without the IE technique can provide an estimate of the impact of weather noise on oceanic mean and variability characteristics. Using the NCAR CCSM (T85 atmospheric resolution) with the IE technique implemented, they have systematically explored the impact of weather noise on the AMOC. They show that weather noise plays a crucial role in maintaining both the mean AMOC strength and its variability. In particular, with the weather noise suppressed the mean AMOC strength is reduced by 25%, and a prominent decadal scale model of variability is eliminated. The reduction in AMOC strength is associated with significant cooling over large regions of the North Atlantic. However, changes in the upper ocean subtropical cells are not strongly impacted by the reduction in weather noise. These results suggest that the STCs are not strongly affected by weather noise, but the AMOC is. These intriguing results have potentially key significance for efforts to better understand both AMOC variability and decadal scale predictability.

While the above studies have used dynamical models, there have also been efforts to develop statistical models for AMOC prediction. Zhang (2008) identified a key fingerprint of AMOC variability through diagnostics analyses of observations and models. Her work suggest that surface height and subsurface temperature in the North Atlantic subpolar gyre and Gulf Stream region can be related to AMOC strength. Mahajan et al. (manuscript in preparation) have conducted analyses of the time series of these quantities in the observations, and determined that a second order autoregressive process best characterizes them. This relationship was then used as the foundation for developing a predictive statistical model for the AMOC. Mahajan et al. have used this statistical model to predict a weakening of the AMOC over the coming decade. The development and use of statistical prediction models is an important complement to dynamical models.

b. Meetings and Programs

Several meetings will be held relevant to the topic of decadal predictability, of relevance to AMOC decadal predictability.

(a) October 12-15, 2009, “The Eighth Workshop on Decadal Climate Variability; Decadal Climate Predictability and Prediction: Where Are We?”. This will provide some assessment of the state of knowledge on decadal predictions in general, with some attention to the AMOC.
(b) November 4-6, 2009, “Workshop on Earth System Initialization for Decadal Prediction”, at Utrecht in the Netherlands. This workshop will focus on comparisons of methods for initializing models for decadal predictions, especially in light of the upcoming CMIP5 coordinated experiments on decadal prediction.
(c) Jan 11-15, 2010, at the University of Miami,“Predicting the Climate of the Coming Decades”.

C. UPDATE ON PROGRAM ACTIVITIES

The report "Implementation Strategy for a JSOST Near-Term Priority - Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change, October 24, 2007, called for program activities in eleven specific areas. The scientific community has made a start on addressing some of these with the projects described in section B above. Those projects are listed in Table 1 and enumerated sequentially for ease of reference. Table 2 illustrates the limited extent to which the currently available resources permit the targeted activities to be addressed. Investments in several have only just begun. For the three activities receiving most attention, legacy investments (those started prior to agency response to the ORPP) account for the bulk of productivity to date. These key activities will require sustained investment as other activities are brought on line.

Table 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 Atlantic	NOAA	5/2007 - 4/2010
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 Miami)	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)	Assessing Meridional Transports in the North Atlantic Ocean	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 Straneo	Collaborative Research: Mode Water Formation in the Lofoten Basin: A Key Element in the Meridional Overturning Circulation	NSF	6/2009 –
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			NASA	
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 - ?
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	

28	Fiamma Straneo (WHOI)	S. Lentz	From rivers to the ocean: the dynamics of freshwater export from Hudson Strait	NSF-OCE	1/2009 - 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

Table 2. Community-wide progress as of November 2010 on research activities recommended in the October 2007 AMOC Implementation Strategy for execution by 2013. Activities "initiated" are those that have received funding commitments, but are only just beginning, "in progress" implies that substantial work has begun, "analysis" indicates that project-specific results are being generated, and "synthesis" implies that results have matured to the point that broader implications are being addressed. Green bars indicate the approximate fraction of progress made thus far. At this early stage in development of the program, much remains to be done to initiate and execute these key activities.

Activity	Initiated	In progress				Analysis				Synthesis			
		0%	50%		100%	0%	50%		100%	0%	50%		100%
Develop an AMOC state estimate or "fingerprint"													
Monitor AMOC transports													
Evaluate coherence and connectivity of AMOC circulation and transports													
Assess AMOC observing systems with ocean models													
Reconstruct AMOC variability and associated property fields													
Model the ocean state during the instrumental period													
Develop longer-term proxies for AMOC variability													
Diagnose mechanisms of AMOC variability and change													
Assess AMOC predictability													
Determine impact and feedback of AMOC variability													
Assess role of AMOC in producing observed changes													

D. RELATED ACTIVITIES TO SUSTAIN

1. ***Required observations and fields***

A number of research questions identified in the Implementation Plan can be addressed by analysis and synthesis of data from current and proposed satellite and in-situ observational programs. 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. Several arrays of in situ measurements are active in the Atlantic, but continuity is an issue. There is now some in-situ measurement activity in the S. Atlantic (in-situ measurements at 34.5S to measure the flow along the western boundary of the basin). The status and progress (or lack thereof) of specific measurements are listed below.

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

- Surface Vector Winds: QuikSCAT is still operational, but after 10 years of operation (8 years beyond its designed lifetime), severe degradation of key components indicates that failure is imminent (likely within weeks). The US NPOESS sensor for wind vectors was cancelled. Plans to launch new US scatterometers are not progressing quickly due to budgetary decisions at NOAA. ESA has an operational scatterometer 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 is operational, but occurrences of problems have increased greatly. The coverage of TRMM is limited to the tropical ocean. The follow-on, NASA's Global Precipitation Measurement (GPM), which will have global coverage, is not planned to be launched before 2013. Effort is needed to retrieve and validate rainfall for extra-topical ocean from microwave radiometers now in operation.
- SST: Microwave sensor AMSR-E on Aqua is operational. A follow-on sensor to obtain microwave (all-weather) SST on NPOESS was cancelled and no replacement for AMSR-E has been funded, however AMSR2 is still planned for launch in 2010 aboard GCOM (Japan). Infrared sensor MODIS is operational. Infrared measurements may be part of the NPOESS satellite to be launched in 2009 or later.
- Air-sea heat flux estimates have relied on the International Satellite Cloud Climatology Project (ISCCP) to calibrate and merge cloud information from an array of international geostationary weather satellites over the past two decades. T he status of ISCCP as an operational data set supported by research funding has been called into question, but the consistent multi-decadal data product is critical to the understanding of ocean heat storage and transport. Observations of the Clouds and Earth Radiant Energy System (CERES) on the Earth Observation System's Aqua and Terra satellites have recently been used to derive surface radiative flux, but the deployment of any

follow-on instrument is uncertain.

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

- Sea level and ocean velocities: Jason-2 was launched in June 2008 and SWOT (a wide-swath altimeter concept for sea level and surface water) is anticipated to be launched in 2016. 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. A working group has been established to flag or correct pressure errors. 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 are being addressed by at least three different efforts worldwide.
- Salinity: Aquarius/SAC-D mission is scheduled for a late 2010 launch (the European SMOS mission was launched in the fall of 2009. (See Heat Storage for Argo status).
- Mass budgets: GRACE is operational and a follow-on is being pursued, but no launch date has been set. ESA's GOCE mission was launched in March 2009 and should improve geoid knowledge at scales less than 200km.

c) *Freshwater boundary inputs*

- Ice cover, advection and melt: An ICESAT follow-on has been funded for further study (tentative launch 2015). ESA's Cryosat 2 (sea ice thickness and ice sheet topography) is scheduled for launch in 2010. (See also Mass budgets)
- Discharge from rivers: Studies continue regarding using altimeters to quantify river discharge.

2. *Proxy records*

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 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 activities*

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. 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/) which 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 recent IPCC assessment 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 studies that will be made publicly available include 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.

Sustained efforts are needed to improve ocean data assimilation systems used to estimate the AMOC state in the past few decades. Multiple studies presented in the 2009 AMOC Conference identified 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 decadal observations in the past contribute to such 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 (see 2008 update).

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. At present, decadal predictions (including those for AMOC) are initialized from ocean states that are not constrained directly by observations through assimilation. CLIVAR has recognized the need to initialize decadal prediction using data assimilation products. The 2009 AMOC conference also identified decadal prediction as a key issue for AMOC research. The impact of the 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 (e.g., presented in the 2009 AMOC conference) 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.

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 coastal currents, and small-scale oceanic convection. 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 representation of many small-scale 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 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. *FY09 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 $6 million in support of AMOC activities (see Table 1). NASA provides over $1.5M 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 and predictability studies, and continues to provide about $750K for targeted AMOC observations. NSF supports AMOC through greater than $3M 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. *FY10 and beyond*

The Ocean Research Priorities Plan Near-term Priorities, including AMOC, remain an Administration/OSTP budget priority in FY10 and also FY11. Congress has not yet approved appropriations for the federal research agencies for FY2010. Thus, agencies will not know their budgets until at least a few months into FY10. After Congressional approval is gained, agency internal allocation decisions will determine actual spending levels for AMOC. The supporting agency programs are on track to continue support of AMOC activities at or near current levels. Both NASA and NOAA solicited AMOC-related proposals for FY10. NSF continues to encourage submission of AMOC proposals for consideration.

F. RECOMMENDATIONS

Legacy and recently-funded projects are being molded into an 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. To date there has been only a modest start on only the most urgent activities. Funding limitations have curtailed development plans, particularly the initiation of a trans-basin monitoring system at one or more latitudes to complement the existing UK system at 26.5°N.

In light of the gaps indentified in this second annual progress report, it is recommended that:

1. The design and implementation of a monitoring system for the time varying strength of the AMOC in the subpolar North Atlantic and subtropical South Atlantic be comprehensively planned this year and then realized in the next several years. It is crucial that resources be provided and coordinated internationally so that these quantities are well measured for a sufficiently long time to provide useful indices of various part of the AMOC system in their own right, and to provide the benchmarks needed to validate ocean state estimation models.

2. AMOC-induced climate signals be identified using existing observations and distinguished from

anthropogenic climate change. Additionally, developing fingerprinting techniques to better characterize AMOC variability by combining model simulations with observations should be supported. Finally, inter-model comparison and model-data comparison projects are required to gain better understanding of simulated AMOC oscillations and its relation to the SST variability in the models. Finally, the linkage between the AMOC and AMO should be further explored.

3. Assimilation and non-assimilation modeling efforts be focused on reaching a consensus on the past variability of the AMOC and on advancing our nascent mechanistic understanding of the AMOC so that such models can be reliably used to guide the optimization of a long-term monitoring system. In particular, it is recommended that we assess our ability to detect AMOC-related climate variability and changes that occurred in the past few decades, for such climatically important quantities as transports and storage of heat and freshwater, air-sea fluxes, as well as SSH and SST patterns, and that we understand the uncertainties of existing estimates and the accuracies required to detect climatically important AMOC-related changes.

4. Studies that explicitly address the impacts of changes in the AMOC on climate-relevant variables such as sea ice, marine ecosystems, sea level, and carbon uptake be supported.

5. Assessments of the impact of existing or hypothetical observations on AMOC-related estimates be supported. Because no comprehensive measurement systems currently exist or are planned that are capable of providing broadscale measurements of the ocean below 2000m, direct assessments of the volumetric heat and freshwater content of the deep ocean makes it difficult to assess the AMOC's role in absorbing the excess heat caused by anthropogenic climate forcing. Thus, an examination of the potential impact of having full-depth measurements, either via ARGO floats or other platforms, should be encouraged.

6. In conjunction with the U.S. Climate Change Science Program (CCSP), a coordinated effort focus on the assessment of the potential predictability of the climate system on decadal time scales and the AMOC's role in that predictability.

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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