U.S. CLIVAR: Climate Variability and Predictability

Progress Report for a JSOST Near-Term Priority

Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change

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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 plan, 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, selected in March of 2008, 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 first 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 the programmatic needs 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 estimates of the time-varying AMOC.

2. An assessment of AMOC's role in the global climate
Although overall progress on this program objective remains in its initial stages, several modeling efforts are now underway. The NOPP Program has chosen three modeling projects: a study of optimal observing systems, an analysis of ocean state estimates for AMOC from US and European assimilation projects and an analysis of MIT-ECCO-GODAE results to design observing systems and understand the sensitivity of AMOC estimates to observing systems. Additionally, efforts to reconstruct AMOC variability using data from existing global observing systems are ongoing.

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.

To fill programmatic gaps we recommend that:

1. The key observational priorities identified in section B1, namely those that support 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. Model-based and data analyses continue with a strong focus on the establishment of a link between AMOC variability and SST changes. This linkage is crucial to our understanding of how AMOC changes impact the climate system. Additionally, 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

3. Assimilation and non-assimilation modeling efforts be focused on reaching a consensus on the past state 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.

4. 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.

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

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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, which is 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 will produce 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 first 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. In these early days for the U.S. AMOC program the design of an AMOC monitoring system is a work in progress.

a. <u>*Currently in place*</u>

i. National

At present, the U.S. AMOC monitoring "system" represents a collection of field programs that were largely 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[1], Co-I: Xiaosu Xie[1]
[1]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[1],
[1]Jet Propulsion Laboratory, Pasadena, CA

SODA: exploring centennial changes in ocean circulation
PI's: 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 Drs. T. Chereskin (SIO) and E. Firing (SOEST).

Shifting attention now to north of 26°N, moored and shipboard measurements are being made along a line 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

Presently, there are no national AMOC-related observational programs in the central subpolar Atlantic, however several U.S. field programs are contributing observations of the exchange flows between the Arctic basins and the Atlantic. One of these is 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

A much smaller measurement effort is underway in Hudson Strait through a collaboration between Fiamma Straneo (WHOI) and Canadian researchers.

In addition to 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 are being proposed this year (P. Fratantoni, M. Rhine, personal communications).

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, but it may be proposed this year (M. Rhine, personal communication).

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.

We propose that 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. 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.

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. 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.

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.

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. <u>*Currently in place*</u>

i. National

Two workshops were convened in 2006 and 2007 to explore issues of AMOC predictability. The first of these, at GFDL in June2006, explored this issue primarily from a modeling perspective. Participants came from NCAR, GFDL and a number of universities around the US. One of the motivations for these workshops was to catalyze efforts within NOAA for decadal variability and predictability research leading to the development of a decadal prediction system. Workshop goals were to summarize aspects of what was known about decadal Atlantic variability, both in terms of observational analyses and physical mechanisms, discuss and assess what might potentially be predictable, discuss strategies for initializing models for decadal prediction, and initiate efforts to catalyze US research on Atlantic predictability and predictions. The GFDL workshop focused on modeling activities. A second workshop was held in January 2007 in Miami to focus on observational aspects relating to decadal and AMOC predictability. Each workshop produced a summary that provided specific recommendations for the development of an AMOC decadal predictability and prediction program in the US (the second workshop report is available at
http://www.usclivar.org/science_status/AMOC/AOML_DecadalWorkshopReport_Final.pdf).

ii. International

An international CLIVAR workshop on predicting the climate of the Atlantic sector on time scales from seasons to decades was organized at the University of Reading, United Kingdom in April 2004. The workshop brought together scientists from North and South America, Africa and Europe. The workshop provided an up-to-date assessment of the state of knowledge concerning the predictability of climate in the Atlantic sector at the time, with particular emphasis on the role of the Atlantic Ocean. It identified gaps in knowledge and in observing systems required for the further development of systems for forecasting Atlantic sector climate, and recommended priorities for future research, observational programs, and development of prediction systems. A full report of the meeting along with a set of recommendations is available from http://eprints.soton.ac.uk/18771/01/icpo_pub_81.pdf. A selection of the key review papers that were prepared for the workshop was published in a special issue of Journal of

Climate (Vol.19, Dec. 2006).

Among the two high-priority future research areas for Atlantic climate prediction over the next 5-10 years that the workshop recommended was the development of systems for decadal climate prediction, incorporating both initial condition constraints and transient boundary forcings, capable of predicting both natural climate variability as well as anthropogenically induced climate changes. It was recommended 1) that the systems make use of existing observational data sets in order to identify which aspects of the oceanic initial conditions most constrain the future behavior of the AMOC, 2) to explore data assimilation methods for initializing decadal AMOC forecasts, and 3) to understand how initial conditions and changing external forcings combine to determine climate evolution on decadal timescales.

Some recent progress toward this goal has been made in European centers and institutes. Smith et al (2007) reported some initial results of the Decadal Climate Prediction System (DePreSys) newly developed at the UK Met Office Hadley Centre. DePreSys takes into account the observed state of the atmosphere and ocean in order to predict internal variability, together with plausible changes in anthropogenic sources of greenhouse gases and aerosol concentrations and projected changes in solar irradiance and volcanic aerosol. Using a set of 10-year hindcasts, starting from the first of March, June, September, and December from 1982 to 2001, global anomalies of annual mean surface temperature were predicted with significantly more skill by DePreSys than by the same system without assimilating the observed state of the atmosphere or ocean throughout the range of the hindcasts. The improvement in predictive skill was attributed to the differences in the initialization and evolution of the ocean. In particular, Smith et al (2007) concluded that the increased predictive skill of DePreSys at lead time longer than 15 months resulted mainly from initializing the low-frequency variability of the ocean heat content in the upper 113 m using the existing ocean observations. However, the study did not analyze the role of the MOC in DePreSys decadal forecast. It remains unclear how important the MOC is in terms of improving predictive skill of DePreSys.

Keenlyside et al. (2008) performed a similar set of decadal hindcast/forecast experiments using the IPCC version of the ECHAM5/MPI-OM coupled general circulation model developed at the Max Planck Institute for Meteorology. Different from Smith et al (2007), only SST observations were used to initialize the coupled model via a simple restoring technique. The results suggest that using only SST can improve the model forecast skill over some parts of the North Atlantic, Europe, North America and northern Africa. They argue that the improved model skill comes from the improvement in initializing the Atlantic MOC, as the coupled model simulation with the SST restoring appears to give a better description of the observed decadal MOC fluctuations. The study, however, is only suggestive at this stage and does not prove that predicting MOC variations is a prerequisite for skillful decadal climate predictions in the Atlantic sector.

As part of the ongoing IPCC assessment process there has also been growing awareness of the potential importance of internal variability of the coupled system on decadal timescales. To this end, a draft protocol has been developed over the last several years that would provide a common experimental design for initialized decadal prediction experiments as part of the IPCC fifth assessment report (AR5) that will be completed by 2013. In this protocol it is anticipated that many modeling centers will perform a suite of decadal scale hindcasts for various ten-year periods, starting at 1960 and extending into the future as true decadal predictions. Output from these experiments will be publicly available, and will therefore form an important database for future work on decadal predictability, including for the AMOC. The two largest US climate modeling centers (NCAR and GFDL) have agreed to participate in this international activity. It is therefore anticipated that a large volume of model output will be made available to the national and international scientific community in the next several years that will be of substantial utility for issues of AMOC predictability.

b. _Gaps_

While there are a number of activities in the U.S. exploring issues of decadal predictability, including the AMOC, there is much room for more focused and coordinated US activities. Many aspects of the predictability problem fall within the purview of the evolving U.S. Climate Change Science Program (CCSP) and our goal here is to focus attention on high priority elements that intersect the AMOC program. In particular, since such activities frequently make use of state of the art coupled models, there is a need for such activities to involve the primary modeling centers in the U.S., especially the National Center for Atmospheric Research (NCAR) and NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). These centers have the critical mass to develop new models and apply them to issues of AMOC and other decadal predictability. The output from such models needs to be publicly available for the university community for analysis, synthesis, and feedback to the modeling centers. A coordinated activity along these lines involving the large U.S. centers (NCAR and GFDL) in concert with university partners is especially needed. As articulated below, a crucial need is for both an assessment of the potential predictability of the climate system on decadal time scales, and for the development of the theoretical underpinnings of the mechanisms of such predictability.

In contrast to our understanding of seasonal climate predictions based primarily on ENSO prediction, theoretical understanding of decadal climate predictions is at an infant stage. We have not yet come to a clear understanding of fundamental physical mechanisms governing the predictability at decadal or long time scales, except that our intuition tells us that any predictability at these time scales can only reside in the slow moving components of the climate system, i.e., the ocean, cryosphere and soil moisture and that anthropogenically climate change and natural variability are likely to be equally important at these time scales. Although modeling studies provide suggestions that the Atlantic MOC may be a primary internal source of predictability, the detailed mechanisms that determine predictability are not clear. There is need for a much more detailed theoretical understanding of whether there are intrinsic oscillating modes at decadal or long time scales, if so, how they operate and are sustained, and if they provide physical basis for decadal climate predictions. In particular, there is urgent need for theoretical studies in the following areas:

1) Physical mechanisms governing low-frequency variability of the MOC: Many coupled GCMs exhibit decadal oscillations of the simulated MOC, but oscillating

characteristics differ from model to model, raising concerns about the fundamental physics of these oscillations and their relevance to reality.

2) Relationship between SST variability and MOC variability: Meridional heat transport is widely perceived as a key mechanism linking MOC variability to SST variability - a key variable for climate prediction. However, meridional heat transport is a vertically averaged measure of horizontal oceanic heat flux. How meridional heat transport changes drive SST changes needs to be further clarified. Furthermore, modeling studies show that MOC-induced temperature changes have well-defined vertical structure. For example, a weakened MOC is associated with a surface cooling in the North Atlantic but a warming in the subsurface ocean. Can meridional heat transport explain the vertical structure of the temperature change?

3) Teleconnection mechanisms linking changes in high latitudes of the North Atlantic to changes in low latitudes and other ocean basins: It is well established that changes in the Atlantic MOC strength can induce regional SST and climate anomalies in high-latitude North Atlantic. How these anomalies spread from the high-latitude to the tropics and other basin is less clear. An improved understanding of teleconnection mechanisms between high latitude and low latitude can provide useful information about the memory of the system and thus help to address important questions, such as what are the most important physical processes that determine the system evolution? and what is the best initialization strategy for predicting climate variation at decadal and long time scales.

4) Predictable dynamics and predictability limits: It is important to identify predictable dynamics at decadal or long time scales and gain theoretical understanding of the factors that limit the predictability. There is also need for theoretical investigations of suitable ensemble techniques for sampling forecast uncertainty for decadal climate predictions.

5) Data assimilation methods for decadal climate prediction: Development of data assimilation methods for initialization of decadal climate forecasts is critically important, particularly assimilation techniques for coupled climate models.

Climate models are one of our best tools for furthering our understanding of the AMOC and its predictability, and yet serious deficiencies remain in these models. Improving these models is thus a central goal. Improvements are needed in several areas. We know that small-scale processes may be crucial for the AMOC, and yet most global models in use today have resolutions of 100 km or larger. A crucial gap is therefore the limited computer power available in the US for such modeling studies, limiting model resolution. This is a crucial gap for furthering our understanding of AMOC variability and predictability.

In addition to resolution, climate models suffer from significant biases in the Atlantic sector, especially in the tropical Atlantic (e.g. the zonal gradient of SST on the equator frequently has the wrong sign). These biases cause problems for assimilation schemes and also compromise forecasts directly. Arguably there has been less attention paid to the resolution of these problems than to addressing similar problems over the Pacific Ocean.

Progress in the prediction of Atlantic sector climate requires that the reduction of biases over the Atlantic is prioritized. Higher resolution models of both the atmosphere and ocean may be a pre-requisite, and improvements to the parameterization of sub-grid-scale processes are also required. Also essential is better understanding of the physical processes that determine regional climate.

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	Peter Minnett (U. Miami)	Chelle Gentemann (Remote Sensing Systems, Inc.)	AMOC: Focused analysis of satellite data sets	NASA	8/2008 – 7/2011
2	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
3	K. A. Kelly (U. Washington)	L. Thompson (U. Washington)	Assessing Meridional Transports in the North Atlantic Ocean	NASA	10/2008 – 9/2012
4	Josh K. Willis (JPL)		Monitoring the Atlantic Meridional Overturning Circulation using a combination of SST, altimeter, and Argo data	NASA	10/2007 – 9/2010
5	James Carton (U. Maryland)	Benjamin Giese (Texas A&M U.)	SODA: exploring centennial changes in ocean circulation	NSF & NOAA	6/2008 – 5/2011
6	P.B. Rhines (U. Washington)	S. Häkkinen (NASA GSFC)	Pathways of meridional circulation in the North Atlantic Ocean	NASA	10/2008 – 9/2012
7	M. O. Baringer (NOAA/AOML)	C. S. Meinen, S. L. Garzoli (NOAA/AOML)	Western Boundary Time Series (WBTS)	NOAA	1/2000 - ongoing
8	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
9	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
10	C. S. Meinen (NOAA/AOML)	S. L. Garzoli, M. O. Baringer (NOAA/AOML); A. Piola[2], A. Troisi (SHN); E. Campos (IOUSP); M. Mata (FURG); and S. Speich (IFREMER)	South Atlantic MOC (SAM)	NOAA	10/2008 - ?
11	J. Toole (WHOI)	R. Curry, T. Joyce, M. McCartney	Line W: A sustained measurement program	NSF & WHOI	5/2003 – 2/2008;

		(WHOI); W. Smethie, Jr (LDEO); J. Smith (Bedford Inst.)	sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39^{o}N		renewed 2/2008 – 12/2013
12	S. Lozier (Duke)	A. Bower (WHOI)	Export Pathways from the Subpolar North Atlantic: Phase Two	NSF	3/2008 – 3/2011
13	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
14	Carl Wunsch (MIT)	Patrick Heimbach (MIT) and Rui Ponte (AER, Inc.)	AMOC observing system studies using adjoint models	NASA	8/2008 – 7/2011
15	Tong Lee (JPL)	Geoffrey Gebbie (Harvard U.)	Variability and Forcing Mechanisms of the Atlantic Meridional Overturning Circulation	NASA	9/2008 – 8/2011
16	George Halliwell (U Miami)	W. Carlisle Thacker (NOAA/AOML)	Observing system simulation experiments for the Atlantic meridional overturning circulation	NOAA	8/2008 – 7/2011

Table 2. Community-wide progress as of September 2008 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.

Stage:	**Initiated**				**In progress**				**Analysis**				**Synthesis**			
Activity	**0%**	**50%**		**100%**	**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 will require resources above those that can be explicitly provided by the US AMOC Program. 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 little measurement activity in the S. Atlantic. 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 operational, with occasional age-related disruptions. ESA has an operational scatterometer with somewhat less coverage and accuracy. The NPOESS sensor for wind vectors was cancelled and no replacement for QuikSCAT has been funded, either for research or operations.
- Precipitation: TRMM is operational and may last into 2009. 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. 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. The 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 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.

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) has been funded for further study. Surface drifter coverage is thin in the tropical Atlantic. Global sea level measurements (part of GCOS) received increased attention after the Indian Ocean tsunamis.
- 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 six lines in the Atlantic. Low-density lines scaled back in favor of Argo. (See sea level above for altimeter status)

- Salinity: Aquarius is scheduled for a May 2010 launch. (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 is scheduled for launch in 2008-2009.

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: SWOT concept being studied (see also sea level). (in situ?)

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.

While model-based 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.

For estimation and predictions of the AMOC it is crucial that we sustain the assimilation activities that optimally use the available observational data both to synthesize available observations (esp. those related to the AMOC program) to provide a reanalysis of past oceanic conditions, and to provide initial conditions for model based predictions of the future behavior of the AMOC. The development of such systems, preferably coupled ocean-atmosphere assimilation systems, is in its early stages, but needs to be sustained and augmented.

E. FUNDING

1. *FY08 project totals*

The administration's plans for funding of the ORPP's four near-term priorities are outlined in appendix A. While $40M was requested for FY08, the omnibus funding bill passed by Congress provided only $11.25M. Agency contributions from related programs nominally brought this up to $17M of which up to $7.2M was designated for AMOC activities. Of that, $4M was expected from NOAA, but budget constraints have prevented NOAA from funding AMOC activities in FY08. The result is that a maximum of only $3.2M is available for AMOC in FY08.

2. *FY09 and beyond commitments to projects*

The administration's request for FY09 is the same as for FY08 --- $40M. However, election year dynamics may result in a continuing resolution until after the presidential election or inauguration. Thus, agencies may not know their budgets until several months into FY09. Pending final FY09 appropriation decisions by the Congress, NOAA expects to fund AMOC activities in FY09 essentially following the FY08 plan described in appendix A.

3. *Program Outlooks*

AMOC proposals received in response to the FY08 NOPP BAA have been evaluated and a subset selected for funding. Announcement of the successful proposals is forthcoming shortly. NSF and NASA will probably fund some new AMOC projects through their routine late FY08 and FY09 calls for physical oceanography proposals. NOAA intends to review proposals received in response to its December 2007 call as soon as funds become available; hopefully early in FY09.

F. SUMMARY AND RECOMMENDATIONS

Several legacy and a few 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. This comprises a modest start on only the most urgent activities. Funding limitations during FY08 curtailed development plans and only a few new projects were funded in the highest priority areas. The bulk of the program consists of projects continuing from previous years.

We recommend that:

a) The key observational priorities identified in section B1, namely those that support 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.

b) Model-based and data analyses continue with a strong focus on the establishment of a link between AMOC variability and SST changes. This linkage is crucial to our understanding of how AMOC changes impact the climate system. Additionally, 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

c) Assimilation and non-assimilation modeling efforts be focused on reaching a consensus on the past state 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.

d) 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.

We focus foremost on sustaining existing efforts as they do not yet constitute full investment required to address the most urgent activities. We urge that FY09 investments be ramped up to at least the levels originally envisioned for FY08 so that all urgent activities as described in the AMOC Implementation Strategy can be pursued. This still leaves several activities to be pursued in the out years as observing system design matures.

APPENDIX A.

As of 03-11-08

Ocean Research Priorities Plan Near-term Priorities

FY 2008 Funding and FY 2009 Budget Request

Charting the Course for Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy identified four Near-term Priorities (NTPs) for which implementation plans emphasizing high priority science have been developed by scientists from academia, foundations and Federal agencies with responsibilities in the oceans. The President's FY 2008 Budget requested $40 million toward the NTPs and the omnibus funding bill provided a portion of this request ($11.25 million). Including contributions from associated programs, up to $17 million can now be made available in FY 2008 to pursue these four ocean research priorities, many of which have become the focus of partnership opportunities among Federal and state agencies and non-governmental entities.

The President remains committed to supporting ocean science to enhance our understanding and inform our use and conservation of the oceans, coasts and Great Lakes. Requests for new funding toward this goal include $40 million in the President's FY 2009 Budget for the four high priority near-term ocean research efforts.

Recognizing the critical importance of the science and interagency cooperation highlighted in *Charting the Course*, the NTPs will be pursued in FY 2008 as follows:

Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change

- Up to $7.2M available.
- Funds anticipated to be disbursed through National Oceanographic Partnership Program (NOPP) in response to August 2007 Broad Agency Announcement, competitive peer-reviewed extramural programs and internal agency programs.

Comparative Analysis of Marine Ecosystem Organization

- Up to $2M available.
- Funds anticipated to be disbursed through call for proposals expected for February 2008 release.

Sensors for Marine Ecosystems

- Up to $4.5M available.
- Funds anticipated to be disbursed through National Oceanographic Partnership Program (NOPP) in response to August 2007 Broad Agency Announcement, competitive peer-reviewed extramural programs and internal agency programs.

Forecasting the Response of Coastal Ecosystems to Persistent Forcing & Extreme Events

- Up to $3M available
- Funds anticipated to be disbursed through National Oceanographic Partnership Program (NOPP) in response to August 2007 Broad Agency Announcement, competitive peer-reviewed extramural programs and internal agency programs.

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