U.S. CLIVAR: CLIMATE
VARIABILITY AND PREDICTABILITY

IMPLEMENTATION STRATEGY FOR A JSOST NEAR-TERM PRIORITY

ASSESSING MERIDIONAL OVERTURNING CIRCULATION VARIABILITY: IMPLICATIONS FOR RAPID CLIMATE CHANGE

October 24, 2007

U.S. CLIVAR Report
No. 2007-2

October 2007

U.S. CLIVAR Office
Washington, DC

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BIBLIOGRAPHIC CITATION:
U.S. CLIVAR Office, 2007: Implementation Strategy for a JSOST Near-Term Priority Assessing Meridional Overturning Circulation Variability: Implications for Rapid Climate Change. U.S. CLIVAR Report 2007-2, U.S. CLIVAR Office, Washington, DC, 20006, 20pp.

IMPLEMENTATION STRATEGY FOR A JSOST NEAR-TERM PRIORITY
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A. Introduction

The Meridional Overturning Circulation (MOC) is part of the global ocean circulation responsible for large interhemispheric and interocean exchanges of mass, heat and freshwater. Here the MOC is defined as the large-scale (on the order of 1000 km), low-frequency (interannual to multi-decadal), full-depth, meridional flux of mass, heat and freshwater. The Atlantic component of this circulation, the Atlantic Meridional Overturning Circulation (AMOC), has long been considered the dominant element of the MOC, in large part because the majority of water masses that compose the lower limb of the overturning circulation originate in the North Atlantic. The AMOC transports mass, heat and freshwater from the mid-depth and upper waters at the southern boundary of the South Atlantic into the northern North Atlantic and beyond into the Arctic Ocean: cold, dense water is returned southward at depth. The AMOC is thought to play an important role in the maintenance of the observed meridional temperature structure in the Atlantic and therefore, if perturbed, the consequences to climate, particularly in the North Atlantic and for the continents surrounding the North Atlantic, could be significant.

Interest in the AMOC has been steadily increasing over the last few years, in large part due to a convergence of studies that have linked AMOC variability with past abrupt climate change, demonstrated the susceptibility of the AMOC to multiple stable states, revealed a freshening of the northern North Atlantic surface waters, and suggested that a rapid weakening or shutdown of the AMOC due to anthropogenic forcing would significantly alter temperature and precipitation patterns over the Atlantic, the Americas and Europe. In particular, the AMOC response to and role in anthropogenic climate change is of concern because of its perceived link to past rapid climate change: AMOC has been invoked to explain rapid changes in the climate during the Pleistocene and the termination of the last glaciation, with less dramatic changes during the Holocene (see the National Academies, Ocean Science Board, 2002 publication: "*Abrupt Climate Change: Inevitable Surprises*"). Because abrupt climate change would be expected to bring substantial disruptions to human and natural systems, an assessment of the possibility of such a rapid change to our modern climate is crucial for efforts aimed at understanding the risks of anthropogenic climate change. In addition, AMOC variability on interannual to decadal timescales, though on a less dramatic scale, has been linked to environmentally and societally important components of the climate system. Both AMOC variability and change are likely to impact sea ice; marine ecosystems; the ocean carbon budget and sequestration; and regional and global sea level.

Despite its potential to generate serious impacts, very little is known about the AMOC and its modulation within the context of the global climate system, primarily because direct observational evidence of its oceanic pathways and variability are rare. Unanswered questions surrounding the AMOC are:

- *What is the current state of the AMOC?*
- *How has the AMOC varied in the past on interannual to centennial time scales?*
- *What governs AMOC changes?*

- *Is the AMOC predictable on 10-100 year timescales?*
- *What are the impacts of AMOC variability and change?*

The current gap in observations of and consequent understanding of the AMOC led the Joint Subcommittee on Ocean Science and Technology (JSOST) to identify as a near-term priority in the Ocean Research Priorities Plan the "improved understanding of the mechanisms behind fluctuations of the MOC, which will lead to new capabilities for monitoring and making predictions of the MOC changes."

This Implementation Strategy is a response to the AMOC near-term priority set by JSOST. The five-year implementation strategy calls for a new inter-agency program that, together with activities from the US Climate Change Science Program (CCSP), will develop the initial components of an AMOC monitoring system and AMOC prediction capability. The program is designed to address the objectives described in the JSOST document and to demonstrate visible progress toward those goals within its lifetime. The recommended activities and foci are consistent with the 2002 National Research Council report and are designed to take advantage of rapidly advancing observing, modeling, and assimilation capabilities, as well as to leverage substantial international investment. Importantly, this Strategy also recommends the creation of an AMOC Steering Committee tasked with guiding program implementation and reporting on program outcomes. The Steering Committee (see section H) will work closely with funding agencies to ensure progress toward the expected program outcomes and will be central to the design of a truly integrated program.

B. Impacts of AMOC Variability

A strong justification for studying the AMOC and its variability arises from its potential impact on our natural environment and its subsequent impact on our society. The Ocean Research Priority Plan identifies the goal of studying the AMOC as motivated by the need to "identify the impacts of MOC change on the ocean, climate, extreme weather events, regional sea-level change, ecosystems and carbon budgets." A direct attribution of changes in societally-relevant physical and biogeochemical conditions to AMOC variability is difficult, primarily because the description and understanding of the AMOC and its variability are in a nascent stage. However, it is possible, and as some evidence now suggests, perhaps even likely that AMOC variability may bring about a range of impacts. These potential impacts are summarized below and described further in Appendix I.

Global model simulations show that under normal conditions the AMOC exhibits free, multi-decadal oscillations in the range of 10-20% of its mean strength. Coupled models indicate that an intensification of the AMOC on multi-decadal and longer time scales results in a warming of the upper North Atlantic Ocean and for the land regions of eastern North America and western Europe; when the AMOC weakens, cooling results for these regions. Moreover, anomalously warm North Atlantic SSTs impact regional precipitation and storminess; lead to increased probability of droughts in North America; create a northward shift in the position of the ITCZ; and tend to reduce the vertical wind shear in the northern tropical Atlantic troposphere, a change that can lead to an increase in the number and intensity of tropical Atlantic hurricanes.

Physical constraints on ocean ecosystems exert control at all trophic levels–from primary producers to zooplankton to fish. For example, ocean primary productivity is believed to be strongly linked to the availability of light and nutrients, the latter of which is believed to be strongly linked to ocean stratification, advective transport, vertical mixing, the subduction of water masses and local upwelling/downwelling–all processes that are susceptible to change with AMOC variability. Additionally, the abundance and distribution of zooplankton and fish are expected to be affected by changes in circulation, stratification, the ocean's property fields such as temperature and salinity, as well as shifts in property fronts. To the degree that AMOC variability impacts any of these mechanisms or property distributions, a change in a local, regional or basin-wide ecosystem is expected.

The ocean plays an essential role in the natural carbon cycle by moderating increasing atmospheric concentrations of CO_2 through the sequestration of anthropogenic carbon in the deep ocean. The ocean uptake and redistribution of CO_2 is influenced by chemical, biological and physical properties (including the salinity and atmospheric winds at the ocean surface) which are themselves variously influenced by the AMOC. To the degree that AMOC variability impacts the uptake and transport of carbon, global and regional changes in both the natural and anthropogenic carbon budgets are expected. Less certain impacts may be associated with changes in ocean biology (and hence the biological-pump of oceanic carbon) through changes in the upwelling of nutrients and ocean acidification.

Changes in the AMOC can also have important impacts on global mean sea level by influencing the rate of melting (or accretion) of land-based ice; by affecting the net uptake of heat by the ocean - and consequently its thermal expansion; through local changes in the rate of heat transfer between the atmosphere and ocean in the North Atlantic; through changes of the stabilization of ice sheets at their margins; and through changes in supply of cold waters to the deep ocean globally. Studies suggest that a slowdown or collapse of the AMOC will tend to at least partially offset radiative warming at the surface in the North Atlantic. While a weakening of the AMOC may slow the rate of global sea level rise by reducing oceanic heat uptake, the weakened ocean circulation would have the opposite effect regionally. For example, an AMOC slowdown would bring about a rise in sea level over the entire Atlantic (except the Southern Ocean), with largest amplitude in the subpolar North Atlantic and Arctic. Thus, the impacts of AMOC variations on global and regional sea level are complex, but important to quantify.

Finally, sea ice cover is an important component of the climate system and an integral component of the Arctic ecosystem. Because the albedo of sea ice is much lower than it is for the open ocean, changes in sea ice cover can result in large changes in the high latitude heat budget, with the potential for positive feedbacks. Changes in the AMOC can be expected to influence sea ice cover both directly through the ocean circulation and indirectly through changes in the atmosphere and the resulting forcing of the ocean. Resulting feedbacks between sea ice extent and the AMOC are likely to complicate the AMOC to sea ice relationship.

In summary, a program that focuses on further characterization–through observations, analysis, synthesis, and modeling–of the AMOC and its predictability will dramatically improve our understanding of the links between AMOC variability and the impacts described here.

C. Program Objectives

This implementation strategy for a five-year study of the AMOC outlines a comprehensive, integrated research program to determine and understand the variations of the AMOC and its predictability. The overall objective of this research program is to investigate the physical variability of the AMOC such that researchers will be able to understand and predict the impact of AMOC variability on regional and global climate, ocean ecosystems, sea level, sea ice and the global carbon budget. Toward this end, this program is centered on the physical aspects of the AMOC and its variability.

The three principal objectives of this program are:

Objective 1: The design and implementation of an AMOC monitoring system

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. Hence, the program emphasizes the construction of one or more measurement systems to yield time series of the state of the AMOC. Recently, it has been shown that trans-basin measurement systems (see RAPID in section E) can continuously monitor the strength and vertical structure of the mass transport of the AMOC. Though such measurements provide new information on the magnitude and time scales of AMOC variability at one latitude, what remains unknown is the meridional connectivity of AMOC variability on different time scales. Thus, a central objective of this program is to build upon the only existing in situ program for monitoring the AMOC–the RAPID-MOCHA Array at 26.5N–by developing and implementing additional critical trans-basin measurements at one or more other latitudes. The full benefit of these additional lines will only be realized, however, with a continuation of global observing systems already in place. In particular, the continuity of the satellite altimeter and ARGO are critical for providing basin-wide coverage of upper ocean velocity, temperature and salinity and a measure of the upper ocean heat storage. Full characterization of the three-dimensional structure of the AMOC, its intergyre connectivity and pathways, will be critical to improving our understanding of the AMOC, but due to funding constraints this program will aim to heavily leverage existing programs (e.g., the RAPID program), as well as partner with collaborators in the European Union, Canada and South American and African countries.

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

Although the AMOC has been invoked to explain past abrupt climate change, a mechanistic understanding of its role in climate change and variability, its linkage to other components of the climate system and, importantly, a quantitative assessment of its impact on climate variability have not yet been elucidated. While there exists substantial and growing evidence that Atlantic SST changes are related to climate changes on a hemispheric scale and numerical modeling studies have demonstrated that the Atlantic SST changes cause the observed climate variations, what has not been shown conclusively is that the observed SST changes are caused by (or linked to) changes in the AMOC. Fluctuations in the AMOC are a leading candidate mechanism that could have generated the observed SST changes, but our current and past observations are insufficient to establish this with a high degree of confidence. Therefore, an important objective of this program is to quantify the role of the AMOC–relative to other factors such as changes in other ocean circulation components, radiative forcing, and other surface fluxes–in generating SST variability, and subsequently, climate variability. In other words, the sensitivity of the climate system to AMOC changes needs to be quantitatively assessed. Of particular interest is the degree to which AMOC variability creates changes in meridional heat transport, and the release of that heat to the atmosphere via surface fluxes. Such an objective will include an improved understanding of the physical mechanisms responsible for the AMOC and its variability, its impact on Atlantic SST changes observed in the instrumental record and their collective impact on the large-scale climate on a variety of time scales.

Objective 3: An assessment of AMOC predictability
An overarching goal in climate change science is to develop a system for predicting the future evolution of the AMOC, including the possibility of abrupt climate change. Such a prediction system would take into account both the natural variability of the AMOC and its response to human-induced climate change. In addition, it must be based on a firm understanding of the physics of the AMOC, advanced models to simulate the AMOC, and observational and assimilation systems to both characterize the state of the AMOC and initialize prediction models. While completely achieving such a goal will likely take considerably longer than the time span of this Program, considerable progress can be made through research focused on the AMOC that complements existing programs such as the Climate Change Science Program (see section G). Objectives of this program include an improved understanding of the mechanisms of AMOC variability and change, including its response to wind and buoyancy forcing, and an assessment of the degree to which AMOC fluctuations may be predictable. To reach these objectives, studies are required that delineate the observing and assimilation systems needed to both characterize the AMOC and provide initial conditions for predictive systems. In addition, the development and improvement of models that appropriately represent processes important for the AMOC are needed. These studies will rely on the continued availability of important data for broad scale model initializations such as the Argo array. The successful completion of this program will bring us much closer to the ultimate goal of a prediction system to forecast the AMOC, advance our mechanistic understanding of the AMOC and substantially improve data assimilation and modeling of AMOC related processes.

D. Program Activities

To meet the program objectives outlined in section C and address the questions in section A, the following activities are recommended:

Develop an AMOC state estimate or "fingerprint"

To describe the past variability of the AMOC, as well as to evaluate AMOC impacts, it is desirable to define a "fingerprint", or characteristic signature, associated with AMOC fluctuations. The "fingerprint" needs to be a quantity or quantities that both modelers and observationalists can use. A relatively simple index of the state of the AMOC is the zonally-integrated meridional streamfunction, readily derived from ocean circulation models; however, current and historical observations are grossly inadequate to establish or verify such an index. In addition, while the streamfunction provides a good integrated description of variations in mass transport, it may not be the best descriptor of, for example, the meridional transport of heat. In addition, to reconstruct the past variability of the AMOC when no direct observations have been made, it will be necessary to develop proxies for the AMOC state estimate. Therefore, a high priority for the program is the development of a multivariate fingerprint of the AMOC that would combine critical descriptors of the circulation and transport of ocean properties with those variables that are (or have been) observed extensively or can be reconstructed from paleoclimate archives; an alternative fingerprint appropriate to the temporal resolution of paleoclimate data is also sought. The identification of such a fingerprint(s) will contribute to the interpretation of

AMOC changes and will improve assessments of the impacts of AMOC variability on ecosystems, carbon cycles and global climate.

Monitor AMOC transports

The development of an AMOC fingerprint and the validation of model reproductions of the AMOC require direct observations of the strength and character of the AMOC in order to demonstrate reasonable fidelity. Hence, this program seeks to quantify the large-scale, low-frequency, full water-column net fluxes of mass, heat and fresh water associated with the meridional overturning circulation, defined here as the AMOC. A comprehensive monitoring system for AMOC transports should incorporate both satellite and in situ observing systems. Assuming continuity of these existing global observations, there is clearly a need for an in situ monitoring system focused on the AMOC. This observing system would be designed to complement the RAPID array at 26ºN (see section G), thereby providing full water-column measurements to evaluate intergyre and interhemispheric connectivity within the Atlantic. With this essential addition, the monitoring system will not only lead to a better understanding of the mean state and variability of the AMOC, but may be used to detect whether an abrupt change in the AMOC is underway. Results from modeling studies, as well as from satellite and in situ observations suggest that AMOC fluctuations tend to retain their coherency over certain meridional regimes, but suffer break points in coherence at key latitudes. Places where AMOC "regime" changes typically occur are the subpolar/subtropical gyre boundary in the North Atlantic and in tropical latitudes spanning the equator. Therefore, a transoceanic line in the subpolar North Atlantic that can capture the net contributions of the overflow waters from the Greenland-Iceland-Norwegian Seas to the AMOC, as well as that from the Labrador Sea, should be a high priority. This measurement system would–in conjunction with the RAPID array–provide a means to evaluate intergyre connectivity within the North Atlantic. Similarly, a measurement system in the South Atlantic to provide an evaluation of interhemispheric connectivity is a high priority. Such an array would monitor changes in the relative contributions of Southern Hemisphere water masses to the upper ocean return flow of the AMOC (i.e., Indian Ocean thermocline water vs. Subantarctic Mode Water and Antarctic Intermediate Water), changes that could significantly impact the temperature and salinity of the North Atlantic over time via changes in interocean connectivity patterns. While it is anticipated that design studies and careful logistical considerations will precede these efforts, it is critical to start the collection of long-term full water-column observations of the AMOC as soon as possible, particularly to leverage the existing commitments to the RAPID program, to choke point measurements of northern overflows and to interocean exchange in the South Atlantic (see section E). For such an ambitious program to succeed, the US will look to extensive collaborations with other nations in the development and implementation of a sustained global observing system for the AMOC.

Evaluate coherence and connectivity of AMOC circulation and transports

A defining characteristic of the AMOC is its intergyre and interhemispheric connectivity that allows for meridional transports across vast distances. Though the AMOC has been portrayed as a simple two-dimensional overturning circulation, recent studies suggest a high degree of complexity in a three-dimensional circulation system that is characterized by intermittency in the North Atlantic subpolar/subtropical gyre connection, strong local recirculations, and a high degree of mesoscale and interannual variability. In order to effectively monitor the changing state of the AMOC, a mapping of the pathways for meridional transports is essential. To understand how properties are transported meridionally, an evaluation of the coherence of meridional transports between gyres and between hemispheres is needed, in addition to an evaluation of the role of eddies in those transports. For example, a reduction in meridional heat transport may be more related to intermittency in the connection between gyres or to local heat storage, than to a simple reduction in volume transport. Instead the connection between gyres may be accomplished by interannual variations in the location of the gyre boundary or by the transport of properties by eddies. The extensive coverage and 15-yr altimetric record is ideal for this evaluation at the ocean surface, along with the increasingly large set of drifter data. Float and ARGO data, alone or in combination with ocean models, can be used to map the complex pathways of the AMOC and to evaluate the coherence of transports of heat and freshwater.

Assess AMOC observing systems with ocean models

Ocean models and/or ocean data assimilation (ODA) products can be used to evaluate the effectiveness of various observational systems for measuring the variability and continuity of AMOC transports. By sampling model output using the characteristics of an observational network, the ability of that observational network to estimate transports as represented by the full model can be assessed. An ocean data assimilation system can efficiently evaluate the degree to which any particular set of measurements contributes to specifying the modeled state of the AMOC by comparing estimates with and without a given set of existing (or simulated/hypothetical) observations. Since the applicability of such experiments to the real AMOC depends on the validity of the model employed, model/data comparisons are a crucial part of this evaluation. Specifically, the ability of models to simulate the observed AMOC pathways and transports should be evaluated. Additionally, the ability of the model to capture the large-scale impacts of AMOC variability should be assessed.

Reconstruct AMOC variability and associated property fields

A variety of historical data sets can be assembled to examine the relatively recent history of AMOC variability. The last decade or two has seen an increase in direct measurements of transports, such as the Florida Current and Oleander time series, as well as nearly 15 years of altimetric sea level. The Aquarius/SAC-D Mission, presently scheduled for launch in 2009, will soon provide global coverage of sea surface salinity. These data can be used alone or with a variety of models to estimate changes in connectivity and in heat and freshwater transports and storage and to suggest mechanisms for such changes. Central to an assessment of AMOC-related heat and salt transports, will be an assessment of the Atlantic's heat and freshwater budgets and their recent history. Past abrupt changes in the AMOC using paleoclimate data have been linked to changes in the freshwater balance and if there is an abrupt weakening of the AMOC in the future, it is likely that it will be caused by changes in the distribution of freshwater. Imposing a conservation of ocean properties, using a simple inversion of observations or incorporating an ocean model, can reconcile sparse property and/or transport measurements, as well as aid the evaluation of the contributions of difficult-to-measure sources, such as stream flow, for the freshwater budget. Time-varying budgets will become an important aspect of specifying the state of the AMOC as properties, such as heat content and salinity, become increasing well measured over large areas of the ocean using satellite and large-scale observing systems, such as ARGO and Aquarius/SAC-D.

Model the ocean state during the instrumental period

The past ocean state and its response to observed changes in atmospheric forcing can be modeled using ocean general circulation models, both with and without ocean data assimilation. Non-assimilating models are particularly useful for examining the relative importance of wind and buoyancy fluxes in forcing changes in the AMOC. Comparisons with available observations can be used to evaluate model accuracy. The response of an ocean model to changes in winds, freshwater, and heat fluxes will likely suggest the need for improvements in the forcing fields or in the model to better distinguish forcing mechanisms. Ocean data assimilation provides a tool to synthesize model dynamics with diverse observational datasets, which are limited in spatial and/or temporal coverage, to produce a hindcast or nowcast of the ocean state. The spatio-temporal interpolation, with error estimates, allows an analysis of ocean dynamics that is consistent with the observations. Comparisons of the products from several ODA systems currently show substantial differences, suggesting that a first task is a determination as to whether the differences are due to deficiencies in (1) the ocean model, (2) the assimilation procedure, or (3) the observations. The outcome will prompt the effort for model improvement and the refinement of assimilation methods, and will assist in the design of observational systems.

Develop longer-term proxies for AMOC variability

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

Diagnose mechanisms of AMOC variability and change

Ocean and climate models, in conjunction with analyses of observations, can be used to assess the relative roles of various physical processes and forcing for AMOC variability and change. Modeled fields under various forcing scenarios will be compared with relationships between atmospheric forcing and ocean variables diagnosed from observations. Such comparisons should motivate both the need for additional or improved observations and modeling experiments and modifications with the goal of isolating the dominant processes and forcing mechanisms. Furthermore, as part of this effort, the representation of key physical ocean processes relevant to AMOC timescales will be identified and improved, based on an evaluation of the accuracy of the simulated AMOC. For example, what is the impact of improved representations of overflows on simulated AMOC variability and change? Improvements in the spatial resolution and coverage of observed ocean and ocean forcing fields may suggest the need for improving processes in the models. The impact of the numerical formulation of the model as well as the impact of increased spatial resolution on AMOC simulation should also be evaluated. Such studies will improve our confidence in model predictions of future changes in the AMOC, including the possibility of abrupt change.

Assess AMOC predictability

Statistical and dynamical models relating forcing fields and ocean response can be used to isolate relevant variables and the sensitivity of the response to changes in forcing. Statistical predictive models, which have historically been the baseline against which dynamic prediction models are tested, would likely incorporate the AMOC fingerprint and anticipated changes in atmospheric forcing. Dynamic models allow one to decipher the predictable and unpredictable aspects of the AMOC and to estimate the spectrum of temporal variability of the AMOC, especially on decadal and longer time scales. Diagnostics on the mechanisms of self-generated internal variability both for the ocean and for the coupled ocean-atmosphere system can guide in the understanding of AMOC variability, specifically to distinguish between coupled modes and ocean-driven modes. These can help distinguish between recent observed changes with decadal time scales and longer-term change originating from anthropogenic forcing. The predictability of the AMOC can be examined using ensembles of perfect predictability experiments or by comparison of model hindcasts with observations. The evaluation may include an estimate of the accuracy of initial conditions or forcing that is needed to realize a useful level of predictability. In analogy with the use of atmospheric forecast models to specify and predict weather, ODA can provide the initial conditions for the forecast by synthesizing a diverse set of observations. Finally, the predictability of interannual-to-decadal changes in AMOC, for which the best observational record exists, may differ from the predictability of the slow response to anthropogenic forcing or an abrupt change, for which the observational record is sparse: an evaluation of the different levels of predictability will be needed.

Determine impact and feedback of AMOC variability

Consistent with the overall objective of the AMOC program, studies that focus on those AMOC changes most relevant to the climate system, sea ice, marine ecosystems, sea level, and carbon uptake are needed. Such studies would employ a variety of tools to understand and predict the consequences of changes in the relevant physical variables such as AMOC pathways, surface and subsurface ocean temperatures, coastal currents and air-sea fluxes of heat and freshwater. A focus of the AMOC program is to relate these physical variables to the AMOC fingerprint in order to provide information for impact studies on a variety of applications. This relationship may at first take the form of correlations between the physical variables and the AMOC state; the first such physical variable would likely be SST. In addition to analyses and syntheses of observations, modeling studies emphasizing the physical aspects of the AMOC that impact marine ecosystems, sea ice, and carbon sequestration as outlined in Section B should be undertaken. For example, if changes in coastal currents are hypothesized to affect fisheries, then in order to provide a realistic scope for this program, a study of the effect of AMOC on coastal currents would be appropriate. However, a study with a primary focus on the effect of the change of currents on fisheries itself would lie beyond the scope of this program.

Assess role of AMOC in producing observed changes

An assessment of the relative role of the AMOC, versus other competing mechanisms, in generating the observed changes in the physical climate for various time scales is needed. While a fluctuating AMOC is a leading candidate mechanism for the generation of the observed SST changes that impact the climate system, analyses of current and past observations have not established this linkage with a high degree of confidence. Thus, it is crucial to quantify the relative roles of the AMOC, other ocean circulation changes, radiative forcing and other surface flux changes in generating the observed SST changes. Improved ocean observations and forcing fields, along with better climate records, can be used to improve confidence in linkages with AMOC. An ocean modeling effort can give a dynamic context to recent and past observations of abrupt climate change. For example, although the abrupt climate changes that occurred during the cool climates of the Pleistocene have been hypothesized to result from changes in the AMOC, a firm relationship between AMOC and abrupt climate change has not been established.

Model experiments characterized by different states of the AMOC can be used to infer the global impacts of the AMOC on ecosystems, sea-level and carbon budgets.

E. Related Activities to Sustain

Required observations and fields

A number of research questions identified in Section A can be addressed by analysis and synthesis of data from current and proposed satellite and in-situ observational programs. Although many of these measurements are critical to the success of an AMOC observing system, particularly for understanding forcing mechanisms and the impact of AMOC changes on the climate system, responsibility for the design and implementation of these observing systems lies with NASA, NOAA, NSF and international partners and is beyond the scope of this AMOC program. Particular quantities that are critical for AMOC studies and the measurements needed for those fields are listed below. We strongly recommend these measurements be sustained.

1. Air-sea fluxes: heat, momentum and freshwater
    - Surface Vector Winds (satellite, moorings, and volunteer observing ships)
    - Precipitation (satellites and moorings)
    - SST (microwave and infrared from satellites, drifters, and moorings)
    - Other measurements needed for improved flux fields (satellite and moorings)

2. Oceanic heat, freshwater and mass transport and storage
    - Sea level and ocean velocities (satellite altimeters, surface drifters, and sea-level stations)
    - Heat storage (ARGO, XBT networks, and satellite altimeters)
    - Salinity (satellite, Argo, and thermosalinograph observations)
    - Mass budgets, including existing programs such as the Carbon/CLIVAR Repeat Hydrography Program, choke point observations such as the measurement of the northern overflows into the North Atlantic (the Denmark and Faroe Bank overflows), measurements of inflows into the Atlantic (e.g., from the Drake Passage and south of Africa) and satellite gravity measurements

3. Freshwater boundary inputs
    - Ice cover, advection and melt (satellite and in situ)
    - Discharge from rivers (satellite and in situ)

Proxy records

In addition to the reconstructions mentioned above, it is recommended to continue with efforts directed toward:

- Ice cover, advection and melt (satellite and in situ)
- Discharge from rivers (satellite and in situ)
- Development of multi-proxy records for the AMOC that constrain the vertical structure and meridional connectivity through time, with an emphasis on times of inferred large changes in the AMOC

- Paleoclimate reconstructions of sea surface temperature, and the development of databases for these reconstructions
- Paleoclimate reconstructions of sea surface salinity, and the development of databases for these reconstructions
- Better quantification of freshwater fluxes over the last glacial cycle including reconstructions of ice sheet melting rates and pathways

Modeling activities

Continuation of general ocean model improvement through respective modeling groups is anticipated and encouraged. The AMOC program will seek participation of these activities to target AMOC-relevant modeling challenges. Additionally, efforts directed toward the development of an AMOC prediction system through, for example, CCSP, will considerably complement the goals of this program.

F. Expected Outcomes and Phasing of Activities

The expected outcomes of this AMOC program are:

1. *The identification of an AMOC "fingerprint" and indices based on observable variables and paleo-proxies (2011-2012)*
2. *An estimate of the current state and variability of the AMOC (2008-2011)*
3. *The design and initial implementation of a trans-basin AMOC monitoring network (2008-2012)*
4. *An assessment of AMOC meridional connectivity and property (e.g. mass, heat, freshwater) transports (2008-2011)*
5. *The identification of mechanisms important for AMOC variability and assessment of AMOC predictability (2008-2012)*
6. *An updated assessment of the risk of rapid change in AMOC affecting our climate (2010-2012)*
7. *The characterization of the role in climate system and potential impacts (e.g., on the climate system, ocean variables, sea level, etc.) of AMOC changes (2009-2012)*

The phasing of the program activities, focused on achieving these expected outcomes, is detailed in the table below.

Activities	2008	2009	2010	2011	2012	2013	Contributes to Outcomes
Observations							
Identify pathways of AMOC and quantify coherence of property transports	░	░	░	░			4
Evaluate existing high-resolution paleo proxies; generate and synthesize new paleo records of Atlantic variability	■	░	░	░	░		2
Assemble and analyze historical Atlantic Ocean data sets; define and refine multivariate fingerprint of AMOC	■	■	░	░	░	░	1,2
Evaluate, enhance and design AMOC observations	░	░	░	░	░	░	3,4
Initiate transoceanic AMOC observing system		░	■	■	■	■	3
Mechanistic understanding							
Evaluate and improve ability of ocean models and ODA to describe observed variability of the AMOC	░	░	░				2,5
Describe history of AMOC variability using observations and models from instrumental period	░	░	░	░			2
Utilize satellite data, in-situ observations and models to identify mechanisms and forcing important for the AMOC variability	░	░	░	░	░	░	5
Identify impacts on carbon, climate, etc. and possible feedbacks associated with AMOC changes				░	░	░	7
Predictability							
Conduct predictability studies and evaluation of hindcasts using observations	░	░	░	░			5
Improve ODA systems for initialization of coupled models used for forecasting		░	░	░			5
Characterize sensitivity of AMOC variability to Atlantic climate forcing		░	░	░	░		6,7
Conduct joint research activities with CCSP on developing experimental AMOC forecasts			░	░	░	░	6
Planning Activities and Linkages							
Strengthen planning coordination with related domestic and international activities	■	■	░				
Coordinate planning with CCSP to develop experimental predictions of AMOC	░	░	■	░			

Table 1. Suggested phasing of AMOC program activities, focused on achieving expected outcomes. Because of uncertainties associated with availability of resources and scientific progress, initiation and phasing of program activities should be reviewed annually by the AMOC Steering Committee and the Science Team. Dark shading is used to indicate the time critical periods for activities that require extensive collaborative efforts and/or that require sequential effort.

G. Linkages to Other Programs

RAPID

The US AMOC program will complement the objectives and scope of the ongoing Rapid Climate Change Program (RAPID and RAPID-WATCH) funded by the United Kingdom's Natural Environment Research Council (NERC). The RAPID Program has funded a mooring array across the North Atlantic near 26°N and some monitoring capability in the subpolar North Atlantic (e.g., the WAVE array near the western boundary). The latter is not adequate for monitoring the integrated meridional transport of mass, heat, and freshwater across high-latitudes. Moreover, no measurement system is in place in the South Atlantic to monitor the lower limb of the AMOC that connects the Southern Ocean with the upper limb of the AMOC in the North Atlantic. The U.S. AMOC program should seek to enhance and extend collaborations with RAPID-WATCH as well as with activities in the South Atlantic region to encourage partnership and cooperation in addressing these needs.

DAMOCLES

Because of the potentially important interaction between the AMOC and sea ice in the North Atlantic, this program has a strong link to EU's DAMOCLES program that focuses on the Artic region. DAMOCLES aims to design a cost-effective and sustainable Arctic Observing and Forecasting System. DAMOCLES provides modeling and observational capabilities in the Arctic region to infer the volume and pathways of freshwater export to lower-latitude North Atlantic, particularly across the Greenland-Scotland ridge. Such knowledge is important to the understanding of the impact of the changes in the Arctic region on the AMOC.

ASOF

The AMOC program will complement activities coordinated by the Arctic-Subarctic Ocean Flux (ASOF) study and its legacy. Of particular interest are the ASOF contributions concerning mass, heat, and freshwater fluxes into the North Atlantic Ocean via the Canadian Archipelago (Hudson Strait, Davis Strait). The importance of continental shelves as conduits for Arctic freshwater anomalies is another area of mutual interest (East Greenland, West Greenland, and Canadian continental shelves).

PIRATA

The PIRATA program is designed to study tropical Atlantic variability and its impacts on climate of the surrounding continents including ocean-atmospheric interactions. The AMOC program will complement these activities by providing analyses of AMOC variability and its impacts on climate globally. The PIRATA program in turn will provide additional data for the study of the upper limb of the AMOC and for determining the relationship between tropical modes of variability and the AMOC.

IOOS

The Integrated Ocean Observing System (IOOS) is a multidisciplinary system that routinely and continuously provides quality controlled data and information from the global scale of ocean basins to local scales of coastal ecosystems. It is a system designed to provide data in forms and at rates required by decision makers to address societal goals. Coordination with IOOS will be important to maximize the effectiveness of the AMOC observational program.

OOI

The Ocean Observatories Initiative (OOI), sponsored by the NSF Division of Ocean Sciences, plans to initiate construction of an integrated observatory network that will provide a new mode of access to the ocean. The OOI has three elements: 1) a regional cabled network, 2) relocatable deep-sea buoys, and 3) new construction or enhancements to existing facilities leading to an expanded network of coastal observatories. Coordination with OOI would be particularly helpful in evaluating coastal impacts of the AMOC. Additionally, AMOC-related moorings could possibly take advantage of OOI infrastructure and developed standards.

POES

The Polar Operational Environmental Satellite (POES) system, operated by NOAA's NESDIS, collects weather-related measurements from polar-orbiting satellites at nearly the same local time each day, currently four times daily. The POES system includes the Advanced Very High Resolution Radiometer (AVHRR) that is used for SST (but cannot see through clouds) and the MSU, which is used for precipitation.

GOES

Geostationary Operations Environmental Satellites (GOES), operated by NOAA's NESDIS, circles the Earth in a geosynchronous orbit. GOES satellite imagery used to estimate rainfall, detect ice fields and map the movements of sea ice will aid AMOC-related studies.

NPOESS

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will merge existing polar-orbiting satellite systems under a single national program. The program is managed by the tri-agency Integrated Program Office (IPO), utilizing personnel from the Department of Commerce, Department of Defense and NASA. It is unclear if any climate measurements (including microwave SST, ocean vector winds, and sea level) will be included on NPOESS platforms. If so, the AMOC program will make use of valuable observations from these platforms.

EOS

The Earth Observing System (EOS) is a major component of NASA's Earth-Sun System Missions. The mission includes a series of satellites, a science component, and a data system supporting a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. EOS is enabling an improved understanding of the Earth as an integrated system. The EOS Project Science Office (EOSPSO) is committed to bringing program information and resources to program scientists and the general public alike.

Decadal Survey

The National Academy of Sciences recently conducted a Decadal Survey for the Earth Sciences ("Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond"). The report noted with alarm the declining funding for new satellite observations by NASA and the reduction in capability for NPOESS. The Decadal Survey recommended restoration of climate measurements to NPOESS and 15 new research missions to be launched in years 2010-2020, including improved measurements of sea level, ocean vector winds, ice sheets and gravity. The AMOC program will take advantage of observations from these new missions as they come online.

GODAE

The Global Ocean Data Assimilation Experiment (GODAE) is a practical demonstration of near-real-time, global ocean data assimilation that provides, regular, complete descriptions of the temperature, salinity and velocity structures of the ocean in support of operational oceanography, seasonal-to-decadal climate forecasts and analyses, and oceanographic research. Coordination with GODAE will be needed to improve operational and reanalysis products and climate forecasts.

European Union 7th Framework Program Activities

The 7th Framework Program called for activities leading to improved understanding of the AMOC. Projects from recent proposals have not yet been selected; however, CLIVAR's Atlantic Implementation Panel has been facilitating communication between US AMOC planning and EU proposal teams and will continue to encourage coordination between these activities.

BASIN

The overall goal of a joint U.S and E.U. program, BASIN (Basin-scale Analysis, Synthesis and Integration), is to "understand and predict the impact of climate change on key species of plankton and fish and associated ecosystem and biogeochemical dynamics in the North Atlantic subpolar gyre system in order to improve ocean management and conservation." The outcomes of the AMOC program, with ocean ecosystems as one of its targeted impacts, will provide the essential information needed to meet the goals of the BASIN program.

US Climate Change Science Program (CCSP)

The AMOC program leverages and supports the broader priority of US's Climate Change Science Program (CCSP) on "Assessing Abrupt Changes in a Warming World". It contributes to CCSP's "Goal 1" to "Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change." It also directly addresses various aspects of "Goal 3", for instance, to "Improve characterization of the circulation of the atmosphere and oceans and their interactions through fluxes of energy and materials" and to "Increase understanding of the conditions that could give rise to events such as rapid changes in ocean circulation owing to changes in temperature and salinity gradients".

Other ORPP Priorities

AMOC effort will improve the understanding of potential impacts on coastal and marine ecosystem as well as hurricane activities. Therefore, it would benefit potential programs addressing other priorities of the Ocean Research Priority Plan (ORPP). Moreover, the ORPP Near-Term Priority calling for improved ocean sensors could address the need for sensors to measure important AMOC components.

IPCC

AMOC will provide in situ measurements, improved synthesis products and proxies reconstructed from paleo records to evaluate the performance of coupled climate models used by the Intergovernmental Panel on Climate Change (IPCC), particularly in regards to long-term changes in the Atlantic. AMOC-derived products will also be used to initialize future predictions and projections.

International CLIVAR

The AMOC program will bolster the efforts of (1) CLIVAR's Working Groups on Ocean Model Development (WGOMD) for model improvement and (2) CLIVAR's Global Synthesis and Observations Panel (GSOP) for model-data synthesis and improvement of ODA systems. Moreover, the AMOC program will capitalize on the advancement resulting from WGOMD and GSOP activities. Finally, the AMOC program will take advantage of the important international coordination role of CLIVAR's Atlantic Implementation Panel. The U.S. CLIVAR program will periodically review progress of the AMOC program as it develops.

H. Scientific Oversight

An AMOC Steering Committee will be an integral component of this program. The overall role of this committee will be to identify relevant research activities and scientific gaps; periodically re-evaluate the priorities of the program; ensure coordination with other programs; assess progress toward program outcomes; and coordinate the production of assessments and other reports required by the funding agencies. Given the scope of this program, on both the observational and modeling front, and the need for international collaborations to meet many of the stated goals, the Steering Committee is expected to play a vital role in coordinating the national and international efforts focused on the AMOC. Another important role for the Steering Committee will be to address how best to achieve an integrated program given the funding potentials and constraints of each contributing agency. In particular, the Steering Committee is expected to aid agency efforts to most efficiently leverage resources by guarding against duplicative efforts within an agency, across agencies, and, importantly, with other national and international efforts.

The AMOC Steering Committee should be comprised of a pool of ~ 8-10 scientists with interest and expertise in the AMOC. Committee members may or may not be funded investigators. The committee should meet semi-annually to foster integration among the various program elements and activities. One task of the Steering Committee will be to plan and coordinate an annual meeting of an AMOC Science Team.

The Science Team, which is to be comprised of all funded investigators, will bear the responsibility of accomplishing the program objectives with guidance and oversight from the Steering Committee. The Science Team may have organized subgroups to better address the program objectives and to facilitate collaboration between research groups. The focus at the annual Science Team meetings will be on the dissemination of recent research results, as well as on coordination of efforts, and identification of evolving science and monitoring issues.

Finally, the US CLIVAR program will undertake periodic review of the AMOC program. The AMOC Steering Committee and Science Team will play a pivotal role in this review by providing reports and assessments, as requested.

APPENDIX A: POTENTIAL IMPACTS OF AMOC VARIABILITY

Climate and Extreme Weather Events

The link between AMOC and regional and global climate variability is based largely on the analysis of global climate model output because direct measurements of the AMOC are rare. Global model simulations show that under normal conditions the AMOC exhibits free, multi-decadal oscillations in the range of 10-20% of its mean strength. Coupled models indicate that multi-decadal and longer-term variations in the intensity of the AMOC result in a warming of the upper North Atlantic Ocean when the AMOC intensifies and a cooling when the AMOC weakens. In most models this change is accompanied by a change of the opposite sense in the South Atlantic. North Atlantic sea surface temperature (SST) changes associated with these fluctuations can be as large as 1°C, with the Labrador, Greenland and Norwegian Seas similarly impacted. The bordering land regions, eastern North America and western Europe, exhibit milder but consistent surface air temperature changes, which are accompanied by changes in the rate of occurrence of temperature extremes. Modeling studies show that a total collapse of the AMOC would cool hemisphere-wide surface air temperatures by as much as 1-2°C on average, with larger amplitude cooling in the northern North Atlantic Ocean (3-5°C) and the bordering continental areas of both western Europe and eastern North America. In its recent assessment of the climatic impact of anthropogenic emissions, the IPCC (see IPCC WG-1 Final Report) issued a carefully worded statement indicating that major changes in oceanic circulation systems (AMOC included) are not expected to occur before the end of the 21st century. However, the IPCC suggested that a significant reduction in AMOC is expected to follow anthropogenic warming, the melting of sea and land ice in Greenland and the Arctic, respectively, and the increase in precipitation over the subpolar Atlantic. This assessment has been challenged by a considerable number of scientists who have suggested that the large gaps in understanding, observing, and modeling the AMOC render such assessment less certain than stated.

The AMOC-related SST changes have been shown in climate models to be associated with precipitation changes over the ocean and surrounding land. A warmer than normal North Atlantic is associated with an increased probability of droughts in North America. Although the latter is primarily governed by low-frequency ENSO variability, multi-decadal Atlantic SST variations modulate the ENSO influence. In the tropical Atlantic, a warm North Atlantic leads to a northward shift in the ITCZ, which brings more frequent springtime droughts to northeast Brazil and more summer rainfall to the northern edge of South America and sub-Saharan Africa. The opposite is true when basin-wide SSTs are colder than normal. Additionally, AMOC-related SST increases appear to lead to reduced vertical wind shear in the northern tropical Atlantic troposphere, a situation that may lead to an increase in the number and intensity of tropical Atlantic hurricanes. It has also been suggested that a stronger AMOC can lead to increased wintertime storminess over the North American eastern seaboard.

In order to understand and predict how AMOC variability and change would impact climate, it is necessary to measure, understand, and model the variability of the AMOC, its relationship to surface forcing and the corresponding physical processes, and its influence on SST relative to other factors such as changes in other ocean circulation components, radiative forcing, and surface fluxes.

Marine Ecosystems

Physical constraints on ocean ecosystems exert control at all trophic levels- from primary producers to zooplankton to fish. The most relevant physical constraints include advective pathways, the strength and pattern of ocean mixing, water column stratification, convergence/divergence of the local and basin-wide velocity fields, and the degree of mesoscale activity. Additionally, the ocean's property fields, principally the distribution of temperature, salinity and nutrients, impact the structure of a regional ecosystem. To the degree that AMOC variability impacts any of these mechanisms or property distributions, a change in a local, regional or basin-wide ecosystem is expected.

Of particular interest is how AMOC variability might impact the basin-scale temporal variability in primary productivity. Ocean primary productivity is believed to be strongly linked to the availability of light and nutrients, the latter of which is believed to be strongly linked to ocean stratification, advective transport, vertical mixing, the subduction of water masses and local upwelling/downwelling – all processes that are susceptible to change with AMOC variability. The abundance and distribution of zooplankton and fish are expected to be affected by changes in circulation, stratification, temperature and salinity, as well as shifts in property fronts.

In order to understand and predict how AMOC variability and changes would impact ecosystems, it would be necessary to measure, understand, and model 1) the intergyre transport of nutrients, 2) the circulation pathways of the AMOC, 3) the impact of AMOC variability on upper ocean stratification and 4) the impact of AMOC variability on local and basin-wide divergence and convergence.

Carbon Budget and Sequestration

The ocean, which plays an essential role in the natural carbon cycle, moderates increasing atmospheric concentrations of CO_2, and hence global warming, by sequestering anthropogenic carbon in the deep ocean. The ocean uptake is accomplished via a carbon flux across the air-sea interface, which is driven by the partial pressure of CO_2 in the ocean and atmosphere and influenced by the local wind speed. This complex process involves chemistry (e.g. dissolution of CO_2 into carbonate and biocarbonate ions), biology (e.g. the consumption of carbon by marine organisms that flux carbon into the deep ocean), and the physical properties in the ocean (e.g. temperature, salinity, and atmospheric wind speed). The AMOC directly transports carbon into the deep ocean and redistributes it globally. Therefore, to the degree that AMOC variability changes the physical constraints impacting the uptake and transport of carbon, global and regional changes in both the natural and anthropogenic carbon budgets are expected.

Changes in the AMOC can be thought of as having direct and indirect impacts on the carbon cycle. Direct impacts include changes in the oceanic carbon transport itself that then change the partial pressure at the surface. Indirect impacts include changes in the partial pressure of CO_2 due to changes in temperature, salinity, and wind speed that may be associated with AMOC changes. Less certain impacts may be associated with changes in ocean biology (and hence the biological-pump of oceanic carbon) through changes in upwelling of nutrients, and ocean acidification.

To better understand and predict the impacts of AMOC variability on the global carbon budget and the ocean sequestration of carbon, it will be necessary to measure, understand and model: 1) meridional fluxes of the AMOC relevant to the carbon cycle leading to improved absolute transport estimates with errors across trans-oceanic sections, 2) estimates of the large-scale ocean velocity distribution with errors to estimate transit-time distributions, water mass ages, formation rates, subduction rates, and ventilation rates as required for improved carbon budget estimates, and, 3) surface changes associated with AMOC variations (such as temperature, salinity and wind speed changes, mixed-layer depth and sea ice changes) to estimate changes in the air/sea CO_2 flux.

Global and Regional Sea Level Change

Changes in the AMOC can have important impacts on global mean sea level through influencing the rate of melting (or accretion) of land-based ice, and by affecting the net uptake of heat - and consequent thermal expansion - by the ocean. Climate model simulations suggest that a slowdown or collapse of the AMOC will tend to offset radiative warming in the North Atlantic, and could therefore delay the loss of the Greenland Ice Sheet and slow the rate of global sea level rise. However, other impacts of an AMOC change, such as an increase in local dynamic sea level, could tend to destabilize the ice sheet through enhanced ice discharge at its margins.

AMOC changes can also impact global sea level through changes in the rate of heat transfer between the atmosphere and ocean in the North Atlantic locally, and through the change in supply of cold waters to the deep ocean globally. For a weakened AMOC, both of these effects would tend to increase the average temperature of the global oceans and enhance thermal expansion and sea level rise.

Superimposed on global mean sea level changes, regional sea level changes may occur due to changes in dynamic sea level related to the ocean circulation. The impacts of an AMOC change on regional sea level distributions will generally include a fast dynamic response of the upper ocean circulation by wave adjustment processes, and a slower response caused by the advection of temperature and salinity anomalies within the changed circulation. The most immediate impact of an AMOC slowdown would be a quasi-instantaneous rise in sea level over the entire Atlantic, with largest amplitude in the subpolar North Atlantic and Arctic, and a corresponding sea level drop in the Southern Ocean, as the meridional pressure gradient associated with the AMOC relaxes.

To better understand and predict the impacts of AMOC variability on global and regional sea level change, it will be necessary to measure, understand, and model 1) the current state of the AMOC, its variability over the past 50+ years during the modern observational record, and its past variability from improved high-resolution paleo-reconstructions, 2) the variability of sea level over the same time scales, 3) the regional dynamic adjustment of sea level to changes in the AMOC, and 4) the sensitivity of global sea level change to AMOC variability, including feedbacks on ice shelf dynamics.

Sea Ice

Sea ice cover is an important component of the climate system, and an integral component of the Arctic ecosystem. Because the albedo of sea ice is much lower than it is for the open ocean, changes in sea ice cover can result in large changes in the high latitude heat budget, with the potential for positive feedbacks. The Arctic region is identified as being very sensitive to anthropogenic CO2 change in most IPCC coupled climate models, and so is an area of particular interest for climate variability.

Changes in the AMOC can be expected to influence sea ice cover both directly through the ocean circulation and indirectly through changes in the atmosphere and the resulting forcing of the ocean. It is expected that increases/decreases in the AMOC will increase/decrease the northward heat transport across the Nordic Sills which will result in a decrease/increase in sea ice cover, although the relative contributions of direct ocean advection and a coupled ocean/atmosphere influence on sea ice has yet to be determined. Changes in atmospheric winds can alter the mass and heat fluxes across the Nordic Sills, and can also directly force sea ice out of the Arctic. This further complicates the relationship between the AMOC and sea ice because the excess transport of the sea ice can in turn influence the AMOC. The interaction occurs through changes in buoyancy fluxes in the deep mixing regions where the upper limb of the AMOC becomes more dense.

In order to understand and predict how AMOC variability and changes would impact sea ice, it would be necessary to measure, understand, and model 1) the northward mass, heat, and fresh water transport across the Nordic Sills, 2) the changes in Arctic atmospheric temperature and winds and their resulting forcing of the Arctic Ocean and 3) ice export from the Arctic.

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U.S. CLIVAR is a contributor to the U.S. Climate Change Science Program (CCSP; http://www.climatescience.gov). International coordination of CLIVAR is organized through the International CLIVAR Project Office (http://www.clivar.org). CLIVAR is a project of the World Climate Research Programme (WCRP - http://wcrp.wmo.int).

The U.S. CLIVAR acknowledges support from these agencies: