Project Summary

Collaborative Research: Overturning in the Subpolar North Atlantic—the Irminger and Iceland Basins

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A US-led international program, Overturning in the Subpolar North Atlantic (OSNAP), designed to provide a continuous record of the full-water column, trans-basin fluxes of heat, mass and freshwater in the subpolar North Atlantic, is proposed herein. The OSNAP observing system consists of two legs: one extending from southern Labrador to the southwestern tip of Greenland across the mouth of the Labrador Sea (OSNAP West), and the second from the southeastern tip of Greenland to Scotland (OSNAP East). The observing system also includes subsurface floats (OSNAP Floats) in order to trace the pathways of overflow waters in the basin and to assess the connectivity of currents crossing the OSNAP line. The location of the OSNAP East and West legs purposefully melds with a number of long-term observational efforts in the North Atlantic: the Canadian repeat AR7W program in the Labrador Sea; the German Labrador Sea western boundary array at 53°N; the global Ocean Observatories Initiative node to be placed in the southwestern Irminger Sea; the repeat A1E/AR7E hydrographic sections across the Irminger and Iceland basins; and the Ellett line in the Rockall region. Substantial international collaboration has been garnered for OSNAP, including measurement contributions from the UK, Germany, the Netherlands and Canada. Importantly, this proposed observing system, in conjunction with the RAPID/MOCHA array at 26^0N and the EU THOR/NACLIM program, will provide a comprehensive measure of the Atlantic Meridional Overturning Circulation (AMOC) and provide a means to evaluate intergyre connectivity in the North Atlantic.

This proposal is specifically for OSNAP East, the OSNAP component that is jointly planned with the U.K. and the Netherlands. Measurements along the composite trans-basin section will consist of a mix of moorings and gliders that will allow for the measure of the net overturning rate in the eastern North Atlantic subpolar gyre resulting from the Denmark Strait and Iceland-Scotland overflows; the subsequent entrainment into these overflows; the net inflow of subtropical waters across the OSNAP East line; the local (i..e., Irminger and Iceland basins) transformation of subtropical waters; and the freshwater transport from the Arctic into the Irminger basin via the East Greenland Current.

Intellectual Merit: For decades oceanographers have understood the AMOC to be highly susceptible to changes in the production of NADW. However, a number of recent observational and modeling studies have called into question this supposition, as more has been learned about the role of wind forcing in AMOC variability. Thus, the overall goal of this work is to establish an observing system that will determine the role that intermediate and deep water mass formation and basin-scale wind forcing play in the overturning and associated poleward heat transport, assessments that currently have only been theorized and modeled, but not observed.

Broader Impact: In January of 2007, the US Joint Subcommittee on Ocean Science and Technology identified the study of the AMOC as one of four near-term priorities in the US Ocean Research Priorities Plan. This proposed work directly addresses that priority via a design of an AMOC observing system in the subpolar North Atlantic. While a primary motivation for studying AMOC variability comes from its potential impact on the climate system, additional motivation for the measure of the heat, mass and freshwater fluxes in the subpolar North Atlantic arises from their potential impact on marine biogeochemistry and the cryosphere. There is growing evidence that the ocean has played (and is playing) a role in the reduction of Arctic sea ice and in mass loss from the Greenland Ice Sheet – both of which have been attributed to changes in the poleward heat transport by the ocean. Also, the ocean plays an essential role in the carbon cycle by moderating increasing atmospheric concentrations of CO_2 through the sequestration of anthropogenic carbon in the deep ocean. Variability in the AMOC is expected to impact this sequestration. Broader impacts with the proposed work also include the training of five graduate students in seagoing operations and in the processing and analysis of observational data.

I. Introduction and background

A. Impact of AMOC on climate, ocean carbon, marine productivity and sea ice

The oceans' Meridional Overturning Circulation (MOC) is recognized as a key component of the global climate system (IPCC AR4 2007). The MOC, characterized in the Atlantic (the AMOC) by a northward flux of warm, saline upper-ocean waters and a compensating southward flux of cool, fresh deep waters, plays a fundamental role in establishing the mean climate state and its variability on interannual to longer time scales. Coupled with the winter release of locally stored heat, the heat advected northward as part of the upper AMOC limb (Rhines et al. 2008) keeps the northern hemisphere generally, and western Europe in particular, warmer than they would be otherwise. Additionally, the AMOC impacts sea level via both steric and dynamic effects: its absence could cause an additional 0.5 m of sea level rise along the North Atlantic coastlines (Vellinga and Wood 2008). Variations in AMOC strength are also believed to influence North Atlantic sea surface temperatures (Knight et al. 2005; Delworth et al. 2007), leading to impacts on rainfall over the African Sahel, India and Brazil; Atlantic hurricane activity; and summer climate over Europe and North America (Knight et al. 2006; Zhang and Delworth 2006; Sutton and Hodson 2005; Smith et al. 2010). Finally, variability of the inflow of warm Atlantic waters into high latitudes has been linked to the decline of Arctic sea-ice (Serreze et al. 2007) and mass loss from the Greenland Ice Sheet (Rignot and Kanagaratnam 2006; Holland et al. 2008; Straneo et al. 2010), both of which have profound consequences for climate variability.

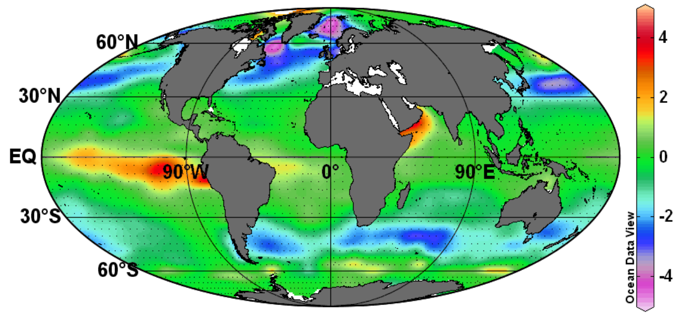

Figure 1. Annual air-sea CO_2 flux ($mol/m^2/yr$; positive out) using gridded data from Takahashi et al. (2009). Courtesy of K. Johnson (MBARI).

Though less studied than its impact on climate, the AMOC's role in the ocean carbon cycle has emerged as a recent concern. The North Atlantic is a strong sink for atmospheric CO_2 (Takahashi et al. 2009), accounting for 41% of the annual mean global air-sea CO_2 flux, with nearly half of that flux occurring north of 50°N (Figure 1). The AMOC is believed to play a strong role in creating this carbon sink: as northward-flowing surface waters cool, they absorb additional CO_2 that is carried to depth when deep waters form. The carbon flux in the subpolar North Atlantic is also driven by a strong, annual cycle of net community production (Kortzinger et al. 2008). AMOC variability can potentially impact this productivity if there is a disruption to the northward flow of nutrients (Palter and Lozier 2008) or to the supply of nutrients to the surface by convection and mixing. Thus, AMOC variability, through its direct impact on CO_2 uptake via overturning or indirectly through its effect on ocean primary productivity, has the potential to alter the ocean's role as a major sink for carbon in the subpolar North Atlantic.

B. Linkage between convection and AMOC variability: climate models

With such a profound array of implications, it is no surprise that a mechanistic understanding of AMOC variability is a high priority for the climate community (Ocean Research Priorities Plan 2007). Opposing hypotheses for the forcing of the overturning have been neatly summarized as "push" or "pull" views (Visbeck 2007), with the former invoking buoyancy forcing at high latitudes as the driving mechanism, and the latter invoking vertical mixing supported by wind and tidal forcing. While theoretical and modeling studies focusing on these opposing mechanisms continue apace (Kuhlbrodt et al. 2007), overturning *variability* has traditionally been linked to the formation of dense water masses at high latitudes in the North Atlantic. Indeed, current IPCC projections of AMOC slowdown in the 21st century based on an ensemble of climate models integrated from 1850 to 2100 with the A1B emission scenario (see IPCC AR4 2007, Figure 10.15) are attributed to the inhibition of deep convection at high latitudes in the North Atlantic. This link between AMOC strength and North Atlantic water mass production was made explicit in a comprehensive study of climate models where freshwater was spread uniformly over the subpolar domain in an attempt to simulate the dynamic response to an external source of freshwater (Stouffer et al. 2006). These “hosing” experiments yielded AMOC decreases, with concomitant decreases in surface air and water temperatures in the high-latitude North Atlantic. However, the adequacy of coarse resolution models to simulate the ocean’s dynamical response to freshwater sources has recently been called into question: Condron and Winsor (2011) argue that the climatic response to freshwater input needs to be studied with models that resolve the dynamics of narrow, coastal flows, an expected source of freshwater in a warming world. As further modeling experiments continue to test the mechanistic link between convective activity and AMOC variability, these efforts must be guided and constrained by observations that substantiate that linkage.

C. Linkage between convection and AMOC variability: observations

Deep convection in the Nordic Seas and in the North Atlantic subpolar gyre (NASPG) produces the water masses in the AMOC lower limb (Figure 2). The deepest constituents of the lower limb originate as dense intermediate waters formed via convection in the Nordic Seas. These waters, referred to collectively as overflow waters (OW), flow over the shallow sills of the Greenland-Scotland Ridge (GSR) into the North Atlantic: to the east of Iceland is the Iceland-Scotland Overflow Water (ISOW), which has traditionally been thought to follow the topography around the Reykjanes Ridge to the Irminger Basin where it joins the deeper, denser Denmark Strait Overflow Water (DSOW). The shallowest component of the AMOC lower limb is the intermediate water produced by convection within the NASPG itself. Though this water mass is referred to as Labrador Sea Water (LSW), it is the product of the cumulative transformation of subtropical waters as they flow around the NASPG.

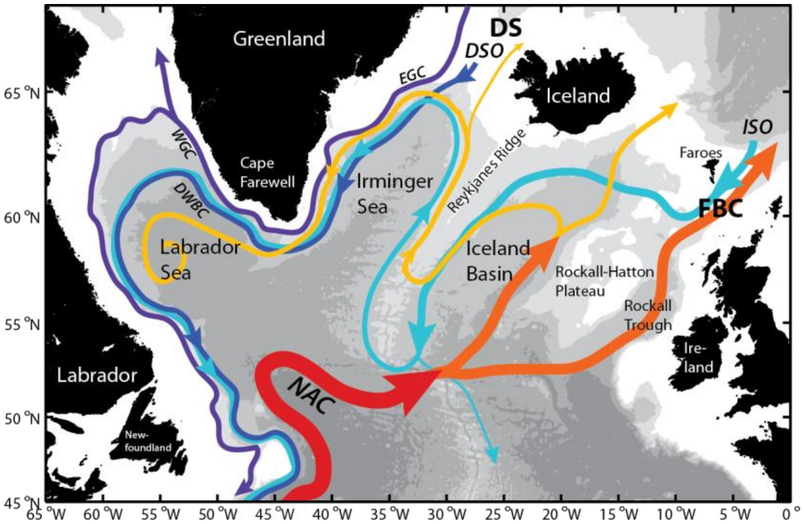

Figure 2. Schematic of the major warm (red to yellow) and cold (blue to purple) water pathways in the North Atlantic subpolar gyre. Acronyms not in the text: Denmark Strait (DS); Faroe Bank Channel (FBC); East and West Greenland Currents (EGC, WGC); North Atlantic Current (NAC); DSO (Denmark Straits Overflow); ISO (Iceland-Scotland Overflow).

1. Past studies of linkage: LSW

As detailed in a recent review (Lozier 2012), no conclusive observational evidence for a link between dense water formation in the Labrador Sea and AMOC variability has emerged to date. Measurements of the boundary currents east of the Grand Banks at 43^0N during 1993 to 1995 and then again from 1999 to 2001 showed that transport in the LSW density range was remarkably steady despite the fact that LSW production was considerably weaker during the latter time period (Clarke et al. 1998; Meinen et al. 2000; Schott et al. 2006; Lazier et al. 2002). Similarly, Dengler et al. (2006) found a *strengthening* of the Deep Labrador Current at 53^0N over the time period of a well-documented decrease in convection. Finally, Pickart et al. (1999) showed that, equatorward of the Grand Banks, the Deep Western Boundary Current (DWBC) appears weaker when it advects a larger fraction of LSW.

2. Past studies of linkage: Nordic Seas overflow waters

Bacon (1998) linked substantial multi-decadal variability in DWBC transport off Cape Farewell (Figure 2) to Nordic Seas atmospheric forcing, with overflow variability as the suggested conduit. A re-examination of the same data (Sarafanov et al. 2009), however, shows DWBC strength to be also correlated with LSW layer thickness. Given the general anti-correlation between dense water formation in the Nordic and Labrador Seas (Dickson et al. 1996), these views underscore the uncertainty regarding the cause of long-term DWBC variability, traditionally presumed to be a measure of AMOC variability.

3. Why is there a possible disconnect between convection and transport variability?
One possible reason for the apparent disconnect between convection and AMOC variability is that not all of the export pathways of dense waters have been monitored. The DWBC has traditionally been considered the sole conduit for the lower limb of the AMOC. However, this assumption has been challenged by recent observational and modeling studies that reveal the importance of interior, as well as boundary, pathways (Bower et al. 2009; Holliday et al. 2009; Stramma et al. 2004; Xu et al. 2010).

Secondly, a direct link between LSW formation and the AMOC has been called into question as more has been learned about the constraints on the spreading of this water away from formation sites (Send and Marshall 1995; Spall and Pickart 2001; Spall 2004; Straneo 2006). Essentially, the compilation of studies over the past decade yields a description of LSW production whereby the properties and transport variability within the DWBC are not a sole function of deep water formation. Instead, boundary current transport, property gradients between the interior and the boundary current and the strength of the eddy field all play a role in setting the exit transport and properties.

Finally, the linkage between AMOC variability and deep water formation can be impacted by wind-driven changes on the overturning itself. Since the density field near the basin boundaries sets the overall shear of the basinwide geostrophic circulation, wind-forced changes in that density field can modify AMOC strength (Hirschi and Marotzke 2007). In fact, AMOC changes on seasonal time scales have been linked to wind-forced Ekman pumping near the eastern boundary of the RAPID/MOCHA line (Kanzow et al. 2010) and similar processes involving Rossby wave transmission of Ekman pumping signals to the western boundary have been implicated on interannual to decadal time scales (Cabanes et al. 2008).

In summary, while modeling studies have suggested a linkage between deep water mass formation and AMOC variability, observations to date have been spatially or temporally compromised and therefore insufficient to either support or rule out this connection. Thus, sustained trans-basin measures of AMOC variability, contemporaneous with measures of dense water mass variability and basin-scale wind forcing, are needed.

D. Current observational and modeling efforts to assess AMOC variability

Although the UK-US RAPID/MOCHA program at 26°N successfully measures the AMOC in the subtropical North Atlantic via a trans-basin observing system, modeling studies over the past few years have suggested that AMOC fluctuations on interannual time scales are coherent only over limited meridional distances. In particular, a break point in coherence may occur at the subpolar/subtropical gyre boundary in the North Atlantic (Bingham et al. 2007; Baehr et al. 2009). A recent modeling study provides context for this lack of coherence (Biastoch et al. 2008): AMOC variability shows a gyre-scale response to variable wind forcing, yet a basin-scale response, i.e. the classical overturning response, to buoyancy forcing. This study also suggests that buoyancy-forced AMOC changes, coherent throughout the basin, have larger amplitude in the subpolar North Atlantic and, as a result, are relatively less obscured by wind-forced signals there, making them potentially more observable.

Results from the RAPID/MOCHA array have made it abundantly clear that strong intraseasonal variability of the AMOC compromises our ability to measure long-term AMOC changes from repeated hydrographic sections. Furthermore, though proxy measures of the overturning derived from satellite altimetry and Argo float data are promising, they are limited by the lack of boundary density observations (Willis 2010). Finally, though it might be expected that the plethora of measurements from the North Atlantic would be sufficient to constrain a measure of the AMOC within the context of an ocean general circulation model, a recent review by Cunningham and Marsh (2010) shows that there is currently no consensus on the strength or variability of the AMOC in assimilation/re-analysis products. Indeed, an active area of research within the climate modeling community is focused on the cause for such wide-ranging AMOC estimates from state estimates that are drawn from the same observational databases (US CLIVAR Report 2011).

II. Program objectives

As evident from the above discussion, there has been to date no purposeful observational measure of the subpolar AMOC, let alone its variability. Thus, we propose a transoceanic observing system in the subpolar North Atlantic, called Overturning in the Subpolar North Atlantic Program (OSNAP), to measure full-depth mass fluxes associated with the AMOC, as well as meridional heat and freshwater fluxes. Given the expected intraseasonal and interannual variability of this measure, we propose sustained measurements for a decade, with the first portion of that time frame proposed herein.

The specific OSNAP objectives are to:

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

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

While we are aware that a decade is insufficient to make clear assessments of the AMOC's response to anthropogenic climate change, previous observations (Yashayaev et al. 2008) suggest there is a high likelihood that significant interannual changes in deep convection will occur during the OSNAP measurement period, allowing an assessment of its linkage to AMOC variability. With regard to longer-term AMOC variability, OSNAP will contribute to an assessment of the critical measurements needed for a multi-decadal observing system and will provide essential ground truth to AMOC model estimates. The intent is to move toward an observing system where a few critical *in situ* observations, coupled with satellite observations and the Argo float array, provide a reliable and sustainable measure of the AMOC for decades to come. While the work proposed herein focuses on the observational system, we fully understand that in order to meet these ancillary goals the larger oceanographic community will need to be engaged. Specifically, modelers focused on North Atlantic data assimilation efforts will be engaged in order to place the subpolar OSNAP measurements in a larger spatial and temporal context.

A key aim of this proposed work is to build a North Atlantic MOC observing system by integrating observations from the RAPID-MOCHA 26.5°N array and from the Nordic Seas exchange across the GSR. Overflows through the Denmark Strait, across the Iceland Ridge and through Faroe Bank Channel, and the inflows west and east of Iceland and west of Scotland have been monitored for decades through research efforts in Iceland, the Faroe Islands, Norway, Denmark and Scotland. Currently, the European Commission's 7th Framework program THOR (Thermohaline Overturning—at Risk?) has been coordinating these measurements and their continuance has been assured through 2017 via the approval of NACLIM (North Atlantic CLIMate) in the spring of 2012. Also, the RAPID observing system, in place since 2004, has been recently recommended for extension to at least 2022. Together, OSNAP, the GSR observations and the RAPID 26°N observational systems provide a means to evaluate intergyre connectivity and to establish a long-term comprehensive observing system in the North Atlantic.

In summary, this proposal focuses primarily on a question of immediate relevance: what is the impact of variable North Atlantic deep water production on the ocean's meridional overturning? That is, are *changes* in local overturning manifest in a temporally variable AMOC? An examination of this linkage is timely since Arctic waters—a dominant source of intermediate and surface freshwater to the Nordic and Labrador Seas—are undergoing unprecedented change (McPhee et al. 2009). The global consequences of these changes, as well as those of global warming, depend largely on their downstream communication via the AMOC.

III. Methodology and approach

A. Overall design strategy

OSNAP is configured as a trans-basin observing system, across which AMOC metrics will be measured using a combination of fixed current meter arrays, repeat hydrographic occupations and gliders. The OSNAP line (Figure 3) consists of two legs: OSNAP West extends from southern Labrador to southwestern Greenland and OSNAP East from southeastern Greenland to the coast of Scotland. Flow through these lines will be connected via subsurface RAFOS floats that will track the pathways of the overflow waters and help interpret observed variability in fluxes across the OSNAP lines. Though alternate configurations were studied, including a single zonal line across the subpolar region, two lines were chosen due to several advantages: water mass transformations and Arctic export pathways west (Davis Strait and Labrador Sea) and east (Fram Strait and Nordic Seas) of Greenland are physically separated; the equatorward evolution of the DWBC and its constituent water masses can be assessed; and the two lines optimize transport calculations since they are nearly normal to the mean flow in the region. This configuration will also allow for detailed studies of water mass transformation within the three sub-basins: Iceland, Irminger and Labrador.

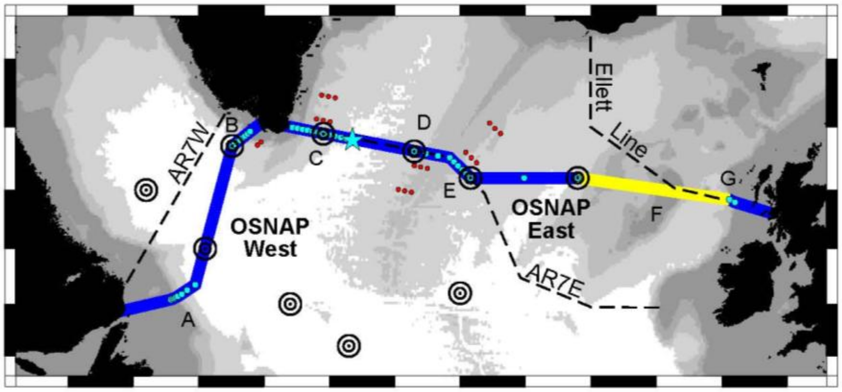

Figure 3. OSNAP elements: (A) German 53°N western boundary array and Canadian shelfbreak array; (B) US West Greenland boundary array; (C) US/UK East Greenland boundary array; (D) Netherlands western Mid-Atlantic Ridge array; (E) US eastern Mid-Atlantic Ridge array; (F) UK glider survey over the Hatton-Rockall Bank and Rockall Trough; (G) UK Scottish Slope current array. Red dots: US float launch sites. Blue star: US OOI Irminger Sea global node. Black concentric circles: US sound sources.

The two legs were situated to capitalize on a number of existing or planned long-term observational efforts in the subpolar North Atlantic: the Canadian repeat AR7W program in the Labrador Sea (although the OSNAP West line has been shifted slightly southeastward to capture the export of all LSW from the Labrador Sea); the German Labrador Sea western boundary mooring array at 53°N; the US Global OOI (Ocean Observatories Initiative) node to be placed in the southwest Irminger Sea; the repeat A1E/AR7E hydrographic sections across the Irminger and Iceland Basins (approximately coincident with OSNAP East); and the Ellett line in the Rockall region.

B. OSNAP design

The proposed observing system design (Figures 3 and 4) is based primarily on studies of past and current observations in the NASPG and secondarily on a series of Observing System Simulation

Experiments (OSSEs). The OSSEs were initially used to explore different experimental designs. For example, an observing system relying heavily on profiling floats was considered, but a study of ARGO float residence times and OSSE simulations revealed that these floats do not adequately constrain flux estimates since the floats execute, on average, just a few profiles in the vicinity of the OSNAP line before they are advected away. OSSEs were also used to validate the final proposed OSNAP design, as will be described below.

Following a consideration of past and current observing systems, as well as a number of OSSE runs, and based on experiences of the OSNAP PIs with NASPG observations, the following design was formulated: Full-depth mooring arrays will be maintained at the continental boundaries, and below the ridge crest on the eastern and western flanks of the Reykjanes Ridge. Additional full-depth moorings containing T/S sensors will be placed at key locations to estimate geostrophic transports. In the eastern basin, a suite of gliders will be employed. Acoustically tracked deep floats will be released on the OSNAP lines to study the connectivity of overflow water pathways between moored arrays and to aid the interpretation of the Eulerian measurements. Design justifications and particulars are explained in subsequent sections.

The effectiveness of the proposed OSNAP design was tested using a series of OSSEs where basin-width integrated fluxes calculated from subsampled model fields were compared to the "model truth" or reference flux. The metric used to evaluate design effectiveness is the monthly-averaged overturning in depth and density space. The model used for these OSSEs is a 1/12°, z-level, regional ocean general circulation model of the North Atlantic that was specially configured to reach good agreement with the observed water mass properties of the NASPG (Böning et al. 2006; Czeschel 2004). The implementation of the OSNAP OSSEs is similar to that used by Baehr et al. (2004) in the study of the RAPID/MOCHA array at 26.5°N (Cunningham et al. 2007), except that the contributions of gliders and current meters are simulated in addition to temperature and salinity moorings. Briefly, the OSSE calculation combines: (i) the directly measured absolute transports from the boundary current meter arrays and deep arrays along the Reykjanes Ridge, (ii) relative geostrophic transport profiles from T/S moorings and gliders in the domains sampled, (iii) estimated Ekman transports from winds, and (iv) a mass conserving reference velocity applied uniformly over all regions not sampled by the direct current meter arrays. An overturning flux for both the model truth and each OSSE are calculated by summing heat, salt and mass fluxes in both z-level and density bins, averaged into monthly mean values.

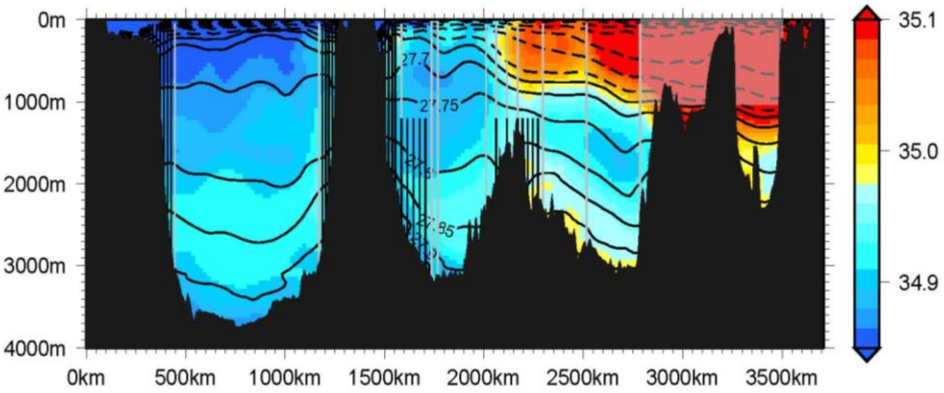

Figure 4. Proposed OSNAP array superposed on climatological salinity along the OSNAP West (leftmost basin) and East lines. Color shading is mean salinity (psu); black solid (dashed) lines are isopycnals at 0.05 (0.10) kg m^{-3} intervals. Proposed mooring locations (vertical lines) and glider domain (shaded box) are indicated. To reconstruct the velocity field, we plan to directly measure the currents at the boundaries and the flanks of the Reykjanes Ridge and then use T/S sensors and gliders to estimate the interior geostrophic velocities. Black moorings indicate where the velocity field is directly sampled. Gray moorings double as direct velocity measures and endpoints for the geostrophic regions.

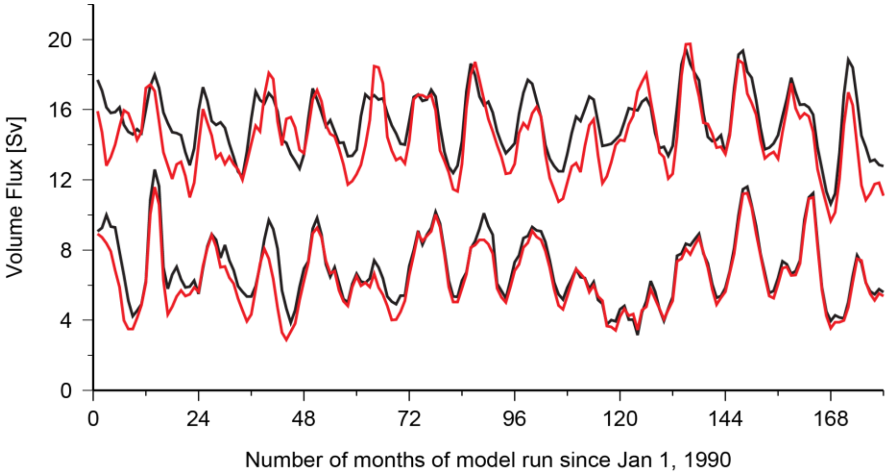

Figure 5. Time series of overturning in density coordinates. Comparison between model truth (red) and OSSE (black) for (upper) OSNAP East and (lower) OSNAP West. The overturning metric is the maximum minus minimum depth-integrated value for the basin-integrated volume fluxes for each 30-day period. The monthly time series has been smoothed with a 3-month box-car filter. Correlation between model truth and the OSSE is .95 (.85) for OSNAP West (East). Unsmoothed monthly correlations are .93 (.80) for OSNAP West (East).

As shown in Figure 5, the OSSE run for the proposed OSNAP measurement system provides good agreement with the "truth" from the model, here shown in terms of overturning in density coordinates. The OSSE mean overturning transports compare well with the reference means: for OSNAP West the reference mean transport in density space is 6.9 ± 2.4 Sv, while the OSSE mean transport is 6.3 ± 2.3 Sv; for OSNAP East the reference mean transport is 15.3 ± 2.2 Sv, while the OSSE mean transport is 14.4 ± 2.7 Sv. Furthermore, the proposed design does an impressive job of capturing the overturning variability. Though we will continue to refine the method for overturning calculations, refinements of the array design (i.e., exact mooring and sensor placements) will be decided heuristically. Further information on the OSSEs is discussed in subsequent sections.

C. Assessment of deep water mass variability

To investigate whether there is a causal relationship between deep water formation and AMOC variability, it is necessary to have robust measures of water mass production. In the Labrador Sea this information will be provided primarily by our Canadian colleagues at the Bedford Institute of Oceanography (BIO, see letters of support). BIO has been occupying the annual springtime WOCE AR7W hydrographic line across the Labrador Basin since 1990. This effort has recently been enhanced with high-resolution XBT sampling; analysis of satellite SSH fields; inclusion of ARGO data and occasional mooring data; and the analysis of surface forcing (NCEP). These enhancements have enabled a yearly assessment of the convective activity in the basin, including the depth, duration, and spatial extent of the convection and the characteristics of the water mass product formed. For the purpose of this study, with its emphasis on the North Atlantic, we plan to link downstream AMOC variability to the measure of the dense waters flowing over the GSR from the Nordic Seas to the open Atlantic. This measure will be carried out during the OSNAP period by the recently-funded North Atlantic Climate (NACLIM) program. In particular, time series of the hydrographic properties and volume transport of the overflows through Denmark Strait and the Faroe Bank Channel will be obtained using a configuration of moorings that has been optimized over the years through previous programs (e.g. THOR). These overflow metrics will be made available to OSNAP investigators (see letter of support from D. Quadfasel). The connection between overflow variability and convection within the Nordic Seas, clearly relevant to the broad questions raised in this proposal, will continue to be addressed within the THOR/NACLIM program. Our investigation of AMOC variability will be considerably aided by this effort.

D. OSNAP coordination

International partners: OSNAP is a US-led initiative with the UK, Germany, Canada and the Netherlands as project partners. Figure 3 is a guide to existing and planned contributions, with details of the international contributions provided in the letters of support (Supplementary Material). In addition to the observations noted in Figure 3, the OSNAP line will be repeatedly occupied by a high-resolution ship-based hydrographic section carried out by the US and international OSNAP partners (Table 1). Plans for data management and for the coordination of ship time for mooring, sound source and float deployments, re-deployments and recovery have been established: details are in Table 1. Additionally, an OSNAP steering committee and an international project oversight committee will be established, the former to facilitate project communication and to coordinate the timing and agendas of both national and international meetings, and the latter to ensure the implementation and success of the observing system by providing an independent assessment of progress. Finally, the US will be responsible for integrating the measurements of OSNAP East and West to produce a continuous record of the NASPG AMOC, as detailed further in this proposal. All participating countries have agreed to a continuous four-year deployment of all measuring arrays, with initial deployment in summer 2014, turn-arounds in 2015 and 2016 and recovery in 2018. The initial 1-year deployments are planned in order to assess adequacy of the arrays, so that any required changes to the program design can be implemented by the start of the 3rd year of measurements.

Table 1. Cruise responsibilities by country. Colors indicate individual cruises. If not specified, "moorings" includes current meter/microcat, dynamic height and sound source (SS) moorings.

	Labrador Basin		**Irminger Basin**		**Iceland Basin**		**Newfoundland Basin**
Month/Year	*Hydro*	*Moorings and Floats*	*Hydro*	*Moorings and Floats*	*Hydro*	*Moorings and Floats*	*SS Moorings (expendable)*
July 2014	UK	US	UK	US[W]; US[E]	UK	US	US
July 2015	US	US	US	US[W]; Neth[E]	Neth	Neth	
July 2016	US	US	US	US[W]; Neth [E]	Neth	Neth	
June 2018	US	US	US	US	US	US	

Graduate student projects: Coordinating efforts will also be focused on graduate student training. All graduate students involved with OSNAP will be trained in the planning and implementation of the seagoing operations (moorings, shipboard data acquisition, floats) during OSNAP cruises, in the processing of observational data, and in the scientific analysis of collected data. Five student projects have been identified: 1) The University of Miami student (supervised by Johns and Bower) will focus on DWBC transport and variability in the Iceland basin and on AMOC/heat transport variability in the NASPG, 2) the Duke University graduate student (supervised by Lozier and Bower) will focus on Lagrangian pathways of the overflow waters using observed and simulated pathways, 3) one WHOI graduate student (supervised by Pickart) will investigate the boundary current system, the overturning and the horizontal circulation of the Labrador Sea, 4) a second WHOI graduate student (supervised by Straneo) will focus on the transport and variability of the East Greenland and Irminger Currents, and 5) the UW graduate student (supervised by Lee) will investigate the fate of Arctic freshwater discharge and its interaction with the subpolar limb of the overturning circulation.

Note: *The rest of this proposal is specific to OSNAP East. A complementary proposal details OSNAP West and OSNAP Floats. Though the float program connects the moored arrays in both OSNAP East and West, it is described entirely in the complementary proposal for simplicity. The broader impacts of this work are described in the project summary and reflected in the synergistic activities of the PIs.*

IV. US OSNAP East Introduction and Objectives

OSNAP East spans the NASPG from Greenland to Scotland. Some of the warm upper-ocean waters transported across this line are cooled and transformed in the Nordic Seas and return to the North Atlantic as dense flows over the GSR sills. The rest is converted to intermediate water as it flows cyclonically around the sub-basins of the NASPG (Figure 2). Major questions remain on the variability of both the deep and shallow parts of this circulation system, and indeed on the adequacy of our understanding of its mean state.

The historical paradigm of NADW formation, where dense overflows of ~3 Sv across the Denmark Strait and Iceland-Scotland Ridge roughly double their net transport through entrainment, leading to an AMOC lower limb of ~13 Sv at Cape Farewell (Clarke 1984; Dickson and Brown 1994; Quadfasel and Käse 2007), has been called into question by recent measurements of Bacon and Saunders (2010). Their year-long array off Cape Farewell yielded a net DWBC transport of only 9 Sv, suggesting that either Clarke's (1984) widely accepted estimate of 13 Sv is wrong, or that there is significant interannual-to-decadal variability in DWBC transport and/or NADW pathways. While there are reasons to question Clarke's estimate (Bacon and Saunders 2010), there is also evidence for significant decadal variability in the DWBC at Cape Farewell (Bacon 1998; Sarafanov et al. 2009) and for multiple DWBC pathways at this topographic break point (Holliday et al. 2009). Thus, whether the hypothesized doubling of overflow transports through entrainment actually occurs and whether this process is stable in time, are, remarkably, unresolved questions.

A developing hypothesis for the interannual and decadal variability of the NASPG upper layer circulation is that wind forcing anomalies lead to variations in the intensity and zonal extension of the NASPG, which in turn cause changes in the advection of warm, salty subtropical waters into the NASPG and Nordic Seas (Hakkinen and Rhines 2004; Hátún et al. 2005; Holliday et al. 2008): a weaker and more contracted NASPG, associated with a low-NAO or East Atlantic pattern of the wind field, causes an enhanced northward flow of subtropical waters that may subsequently impact deep convection. The dramatic increase in salinity of the North Atlantic inflow to the Nordic Seas during the last decade is believed to be linked to this process (Hátún et al. 2005). Variability in the warm subtropical inflow into the NASPG has also emerged as a plausible trigger for the recent acceleration and retreat of glaciers in southern Greenland that doubled Greenland's contribution to sea level rise (Rignot and Karagantnam 2006). This hypothesis is supported by the fact that the glacier retreat began as waters of subtropical origin accumulated in the NASPG (Holland et al. 2008; Motyka et al. 2011) and by recent studies showing that these waters regularly reach the glaciers (Straneo et al. 2010, 2011 and 2012). These studies raise the question of how AMOC, ice sheet and sea-level rise variability are linked on interannual and longer time scales.

Similarly, links between AMOC and the Arctic freshwater inputs have not been quantified. There is abundant evidence that freshwater anomalies exported from the Arctic can circulate around the NASPG (Belkin et al. 1998) and contribute to the shutdown of convection (Lazier 1980; Gelderloos et al. 2012) and/or in the freshening of the intermediate and dense waters (Curry and Mauritzen 2005) (See also Dickson et al. 2008). However, understanding the AMOC response to these freshwater changes is problematic given the absence of long-term measurements from the East and West Greenland shelves (Dickson et al. 2007) where these waters are confined.

Therefore, the specific objectives of OSNAP East are to:

1. Quantify the overturning circulation of the eastern NASPG and the associated heat and freshwater fluxes on monthly to interannual timescales, in depth and in density coordinates.
2. Determine the relationship between overturning strength and the transport of Denmark Strait and Iceland-Scotland overflow waters.
3. Determine the net inflow of subtropical waters across the OSNAP East line and the associated heat and freshwater fluxes to the eastern NASPG.
4. Assess overturning sensitivity to variations in Arctic freshwater input and to wind and air-sea buoyancy forcing

V. OSNAP East design

As mentioned in section III.B, the OSNAP East design (Figures 3 and 4) has been conceptually validated with OSSEs performed using the 1/12° FLAME model. As a companion to the time series of the overturning in Figure 5, a comparison of the vertical structure of the mean overturning circulation in

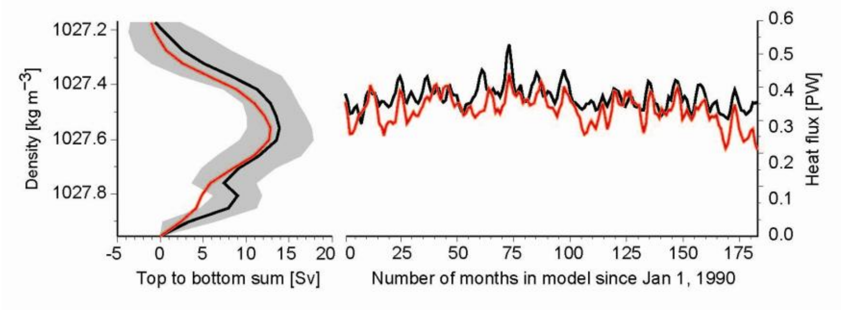

Figure 6. (Left) Mean overturning streamfunction in density coordinates across OSNAP East. Model truth (black line) and its two standard deviation envelope (gray shading) and OSSE result (red line). (Right) Monthly time series of net heat flux across OSNAP East, smoothed with a 3-month boxcar filter.

density space for the OSSE and for the model truth is shown in Figure 6: the comparison is favorable in structure and in the mean. The OSSE is also able to recover the signal of net heat and freshwater flux across the OSNAP East line. The mean net heat flux is 0.35 ± 0.05 PW in the OSSE and 0.39 ± 0.05 PW for the model truth. Mean net freshwater fluxes, relative to the section-width mean salinity of 35.04, also compare favorably, with 0.29 ± 0.05 Sv for the OSSE and 0.28 ± 0.05 Sv for the model truth. As for variability, the net heat (freshwater) flux has a correlation of R = 0.66 (0.89) between the model truth and the OSSE, with respective rms errors of 0.04 PW and .02 Sv (Figure 6 for heat flux only; freshwater flux time series are highly correlated). These correlations are considered conservative since model subsampling in the boundary was uniform whereas mooring placement will be optimized to measure the strongest flows. Sensitivity experiments show that volume, heat and freshwater flux correlations can fluctuate by ~0.1 depending on model mooring placement. Finally, though not included in these OSSE simulations to date, we expect to combine available ARGO data with the mooring data to improve the calculation of the heat and freshwater fluxes.

US contributions to OSNAP East, which include moored arrays in the Irminger and Iceland Basins, hydrographic occupations and the overall integration of OSNAP observations, are detailed in the following sections. Note: In the ensuing discussion, ISO/DSO are used to denote the overflow waters exiting across the GSR, while ISOW/DSOW are used to denote the water masses following entrainment.

VI. Irminger basin: Fiamma Straneo (WHOI)

Flow around the Irminger basin is primarily cyclonic, with fast currents along Greenland and the western flank of the Reykjanes Ridge and a weak interior recirculation known as the Irminger Gyre (Lavender et al. 2000; Våge et al. 2011). In the upper layers, the Irminger Current carries relatively warm waters around the Irminger and Labrador Seas, where they are transformed into LSW (McCartney and Talley 1982; Straneo 2006). Along the Greenland shelf and slope, these warm waters interact with fresh Arctic waters transported by the EGC and the East Greenland Coastal Current (EGCC) (Bacon et al. 2002; Sutherland and Pickart 2008), through frontal instabilities and strong topographic steering by troughs on the shelf (Sutherland and Cenedese 2009). At intermediate depths, LSW formed in the Labrador Sea mixes with a similar, locally-formed water mass (Pickart et al. 2003; Straneo et al. 2003). At depth, ISOW flowing northward along the Reykjanes Ridge encounters the DSOW that spills across Denmark Strait and plunges into the Irminger Basin giving rise to entrainment (Käse et al. 2003), eddy generation (Krauss and Käse 1998) and a dense spill-jet (Pickart et al. 2005). In addition, the Irminger basin lies along the North Atlantic storm track whose interaction with Greenland's mountains gives rise to a complex combination of tip jets, barrier and katabatic winds that force air-sea exchange both on the shelf and in the basin's interior (Moore and Renfrew 2005; Klein and Heinemann 2002). As a gateway for the interaction of Nordic/Arctic and subtropical water masses and through local transformation, the Irminger Sea is thus a key contributor to AMOC variability. Specific questions addressed by the OSNAP Irminger Basin measurements are:

- What is the net entrainment into the DSO and its contribution to the AMOC? This question will be addressed in collaboration with the NACLIM efforts in Denmark Strait.
- How do changes in the local forcing and in the large scale NASPG, including freshwater export from the Arctic and Greenland, influence water mass formation and transformation in the Irminger Sea?

- What is the transport leakage in different density classes around Cape Farewell which, so far, has been only diagnosed from hydrography (Holliday et al. 2007 and 2009)? This question will be addressed by comparing the East and West Cape Farewell array data and trajectories from OSNAP Floats.
- How does freshwater transport at Cape Farewell East compare with the upstream source at Fram Strait (measurements by Hansen, NPI), estimates of Greenland Ice Sheet input (from ice flux and model studies, e.g. van den Broeke et al. 2009) and the freshwater transport observed on the other side of Greenland by OSNAP West?

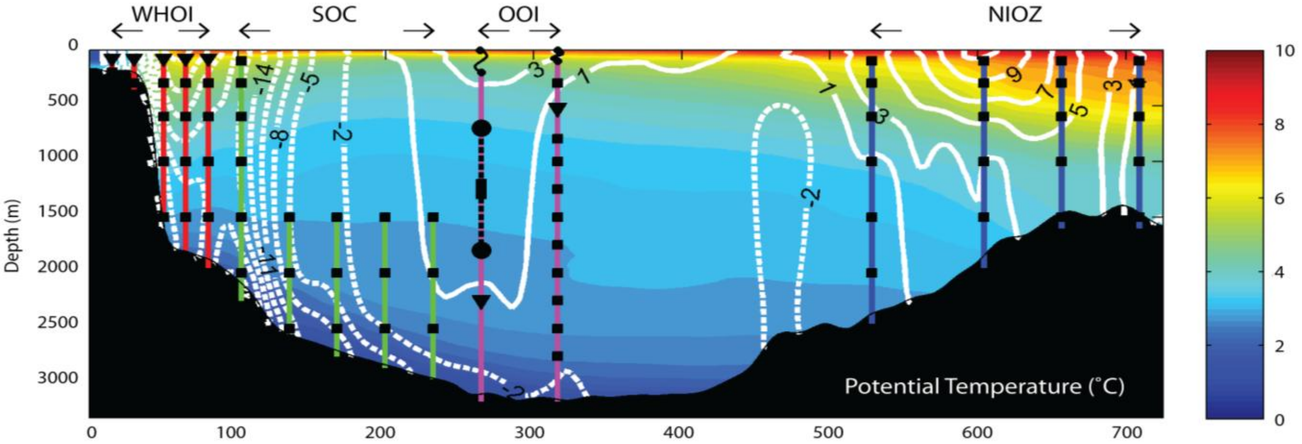

Figure 7. Climatological potential temperature across the Irminger Basin with absolute geostrophic velocity (perpendicular to section from Våge et al. 2011) overlaid. Proposed Irminger basin array includes (west to east): 7 WHOI moorings (red; 5 shown, the other two are farther in on the shelf), 5 UK/SOC (green), 1 profiling and 1 flanking OOI mooring (magenta) and 4 NIOZ moorings (blue). Black squares show T/S and current meter pairs, triangles ADCPs. OOI profiling mooring includes a subsurface profiler and an upper winched profiler.

To address these questions, an Irminger Sea observing system, consisting of a moored array aimed at directly capturing the heat, freshwater and mass transports around the basin, is proposed. Specific targets for these arrays are: (1) the northward flowing branch of warm subtropical water and modified ISO along the western flank of the Reykjanes Ridge; (2) the Arctic freshwater in the EGC and EGCC; and (3) the Irminger Current and modified DWBC along the Greenland slope. The array consists of the following components:

East Cape Farewell Slope Array (Straneo, US): A total of seven moorings, four on the shelf and three on the slope, will be deployed as part of this proposal, to cover both the Irminger and East Greenland Currents (Figure 7, only 2 of the 4 shelf moorings are shown). The four shelf moorings will be deployed in ~200m of water, across the shelf (~50-60 km) to resolve both the inshore EGCC and main EGC branch. They are designed to maximize data return in this iceberg-covered shelf and will consist of a bottom mounted CTD, an upward looking ADCP and an ICECAT at 50 m (a weakly linked CTD inductively connected to a data logger on the bottom that can withstand moderate blow down by icebergs but will break before the entire mooring is dragged). In the event of ICECAT loss, data will be recovered from the data logger. This setup has been successful in comparable environments such as Davis Strait and will be built by C. Lee (UW). The three slope moorings will cover the strongly baroclinic flow (Våge et al. 2011; and Figure 7) and, in particular, the warm water branch. They will carry discrete CTDs (SBE37 SMs) and current meters (Nortek Aquadopps) at fixed depths (tentatively 300, 500, 700, 1000, 1500 and 2000 m) where appropriate. The slope moorings will terminate 100 m below the surface with a CTD and an upward looking ADCP to obtain the upper ocean velocity. Measurements from nearby moorings (see below) and remote sensing products will be used to fill in the T, S properties of the upper 100 m.

Cape Farewell East – Offshore (S. Bacon, UK; See letter of support in Supplementary Documentation): Five moorings (one tall and four ending at 1500 m) carrying discrete CTDs and current meters will be deployed by the UK team offshore of the slope array (Figure 7). These moorings will cover the DWBC and build on the earlier deployment of Bacon and Saunders (2010). The tall mooring will, in addition, allow us to bracket the offshore extent of the strongly baroclinic upper layer flow.

OOI Moorings: OSNAP will request through NSF that the Global Irminger Node of the US Ocean Observatories Initiative (OOI) be sited on the OSNAP line roughly in the center of the Irminger basin. The new location has been received favorably in discussions with R. Weller (OOI PI) and U. Send (Irminger Node Project Scientist). Two moorings from the OOI node will be part of the OSNAP array (Figure 7), a profiling mooring (equipped with McLane Moored Profilers and a surface winched system) that will sample T/S and velocity throughout the water column and a flanking mooring, equipped with 12 T/S sensors and an ADCP. These moorings will allow us to extend the array to cover the Irminger gyre, and provide an eastern boundary for the DWBC transport measurements. They do not require additional instrumentation from OSNAP and are scheduled to be deployed in 2014, at the same time as OSNAP is scheduled to start. Furthermore, additional air-sea fluxes and biogeochemical measurements from the Irminger Node will provide a broader context for OSNAP measurements.

Western Reykjanes Ridge (de Steur, Netherlands; See letter of support in Supplementary Documentation): Four tall moorings carrying discrete CTDs and current meters will be deployed along the Reykjanes Ridge western flank to capture both the upper and deep flow. The array design builds on NIOZ's past and ongoing work in the Irminger Sea which includes the deployment of moorings both in the interior and on the Reykjanes Ridge's western flank. The NIOZ array has already been funded as part of NACLIM and will be deployed in conjunction with the Iceland basin moored array (see Section VII) and follow the same deployment schedule, enabling cost saving through shared ship time (see Table 1). In addition, NIOZ will be maintaining a profiling mooring near the gyre's interior, close to the proposed location of the OOI Node (LOCO2). In the event that the OOI node is delayed and/or malfunctions, the NIOZ mooring will be our backup extension of the East Cape Farewell array to the gyre center.

Design of the full Irminger basin array is based on recent studies including climatological property and velocity sections of Våge et al. (2011) and recent French and UK moorings east of Cape Farewell. Measurements from these moorings (Daniault et al. 2011a,b; Bacon and Saunders 2010) have been instrumental in determining the vertical and horizontal spacing of the proposed arrays. As part of OSNAP, we plan to collaborate with the French OVIDE group (see H. Mercier's letter of support) to jointly analyze the moored data and to take advantage of the OVIDE scientists' experience in estimating overturning across the OVIDE line (Cape Farewell to Spain; Lherminier et al. 2007, 2010). We also plan to work with C. Schrum (GFI, NO) and H. Soiland (IMR, NO), who will be continuing the repeat ADCP measurements from a cargo ship between Denmark and Nuuk ~ along the OSNAP East line (Knutsen et al. 2005). Finally, we intend to work toward collaboration with Russian scientists (A. Sarafanov, Shirshov Institute), who have been making annual hydrographic surveys across 59.5°N since 2002.

VII. Iceland basin: Bill Johns (University of Miami) and Amy Bower (WHOI)

The upper ocean transport of relatively warm and salty waters through the Iceland Basin is estimated to be ~ 15 Sv, with ~ 4-5 Sv ultimately feeding into the Nordic Seas, and the remainder recirculating cyclonically in the Iceland Basin (Saunders 1982; van Aken and Becker 1996; Bacon 1997). A smaller part of the net northward flow (2-3 Sv) occurs in the Rockall Trough, mainly in the Scottish Slope Current (Ellett and Martin 1973; Krauss 1995; van Aken and Becker 1996). An important question to be resolved is how the relative strengths of the Iceland Basin and Rockall branches change interannually in response to changes in the strength and zonal extent of the NASPG (e.g., Hátún et al. 2005). Regarding the deep transport, there remains a crucial question about the amount of entrainment into the ISO: Saunders (1996) measured a transport of 3.2 ± 0.5 Sv in the ISO DWBC southeast of Iceland, essentially the same value as flowing over the sills (~3.0 Sv; Hansen and Østerhus 2007; Olson et al. 2008). While it might be questioned whether this measurement was far enough downstream from the sills to capture all of the eventual entrainment (McCartney 1992; van Aken and Becker 1996), Saunders (1994) also found a transport of only 2.4 ± 0.5 Sv through the Charlie Gibbs Fracture Zone (CGFZ), where the bulk of ISO is thought to pass through the Mid-Atlantic Ridge (MAR) into the western basin. This estimate is lower than some previous estimates based on hydrographic data and is presently being re-measured with a more comprehensive and longer-term current meter array by co-PI Bower; some ISO may also pass through the MAR upstream of the CGFZ (e.g., Xu et al. 2011), but probably not more than 1 Sv. Thus, at present there is little *direct* evidence of significant ISO transport increase through entrainment, unlike the DSO transport that approximately doubles through entrainment (Dickson and Brown 1994).

Specific questions to be addressed in the Iceland basin are:

- What is the net entrainment into the ISO and the corresponding net contribution to the deep limb of the AMOC? (Note: This question will be addressed in collaboration with the NACLIM efforts). How does this contribution vary interannually and how does it link to DWBC variability at other points around the NASPG to be measured by OSNAP?
- What is the variability in the branching of the NAC through the Iceland Basin and Rockall Trough toward the Norwegian Seas? How does the relative strength of these two branches, and the composition of waters carried in them, vary in relation to wind stress curl and buoyancy forcing over the NASPG? Is variability in this branching related to changes in the AMOC? Furthermore, how do changes in the relative strengths of these branches impact the northward heat transport?

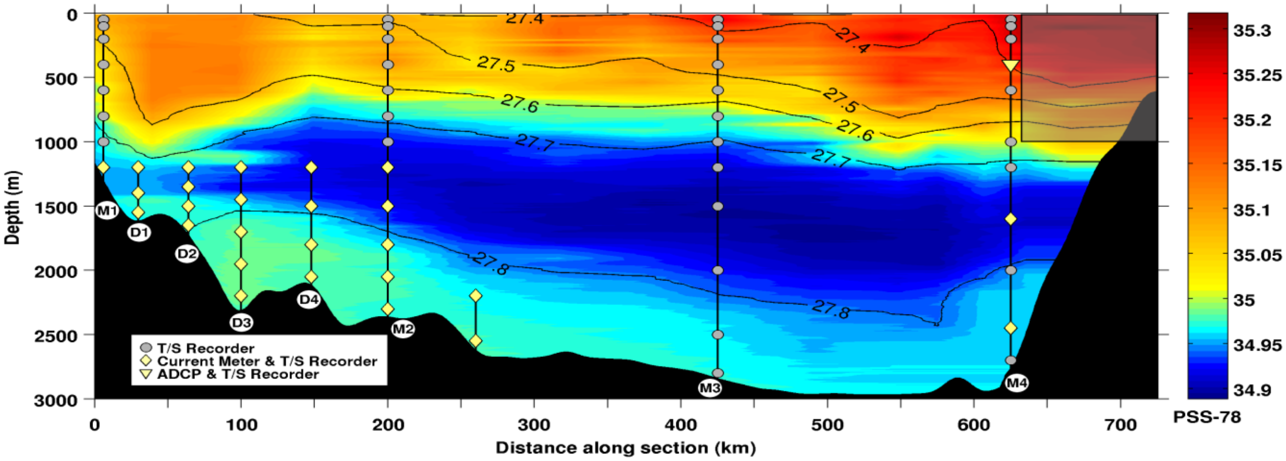

Figure 8. Proposed Iceland Basin mooring array, superimposed on salinity from the 1991 Dutch AR7E section (van Aken and de Boer 1995). Density contours (σ_θ in kg/m^3) are in black. At left is the Reykjanes Ridge crest; at right is Hatton Bank. Hatched area near Hatton Bank indicates the coverage of the UK glider program. ISOW, relatively high-salinity water underlying the relatively fresh LSW at intermediate depths, can be seen hugging the deep eastern slope of the Reykjanes Ridge.

To address these questions, the Iceland Basin array is designed to capture several key elements of the NASPG: (1) the DWBC along the eastern flank of the Reykjanes Ridge, composed of ISOW and its entrainment products; (2) the northward flow of upper ocean waters transported by the main branch of the NAC; and (3) the southward recirculation of the Iceland basin sub-gyre of the NASPG along the eastern flank of the Reykjanes Ridge. The array consists of the following components:

Basin-wide array: The proposed Iceland Basin array includes four full-water column "dynamic height" moorings (DHMs) carrying vertical arrays of moored T/S sensors (Figure 8). The DHMs will monitor the relative geostrophic transports over the three respective mooring spans, which correspond physically to the southward-flowing upper ocean "western boundary current" of the Iceland Basin sub-gyre (between M1 and M2), and the broader northward flow of the NAC in the eastern part of the basin (between M2 and M4). The main part of the northward NAC flow in the Iceland Basin is expected to occur in the easternmost region between M3 and M4, and that, coupled with the zonal gradients in water properties, requires the two mooring spans in the east in order to accurately calculate the meridional heat and freshwater transport. The method for estimating geostrophic transports from these moorings will follow similar methods developed for the RAPID-MOCHA program at 26.5°N (e.g., Johns et al. 2005; Kanzow et al. 2010). For the Iceland Basin, approximately 12 T-S sensors are required to obtain sufficient (~1 Sv) accuracy in the relative geostrophic transports across the mooring spans; the distribution of these sensors (Figure 8) will be optimized prior to deployment.

The eastern end of the array (at M4) will link to the UK-OSNAP glider sampling across the Rockall-Hatton banks, where one glider will patrol the upper slope region west of Hatton Bank including repeated profiles in the vicinity of M4 (for redundancy in case of loss of the upper part of M4). An upward-looking ADCP at 400 m and several deeper current meters will be installed on M4 to monitor the transport in the topographic wedge between M4 and the Hatton Bank should there be any gaps in the glider coverage there. The deeper currents at M4 are also of interest because of evidence from water properties of a deep eastern boundary current off Hatton Bank bringing Lower Deep Water (a modified form of Antarctic Bottom Water, McCartney, 1992) northward into the Iceland Basin.

Deep Western Boundary Current array: The DWBC array in the Iceland Basin includes four deep (>1200 m) moorings D1-D4, carrying current meters and T-S sensors, and deep instruments on the bracketing M1 and M2 (Figure 8). This array should capture the entire transport of the DWBC (found between depths of ~1200 and 2200 m by Saunders (1996) at 63°N). Initially, we plan to deploy one or two additional moorings with near bottom current meters farther down the slope (at ~2800 m) to be sure that the full extent of the DWBC has been captured. The array design and instrument spacing on the moorings is based on Saunders' (1996) measurements and existing high-resolution topography from multi-beam data. Each of the current meters will have T-S sensors mounted alongside them so that the transport in various density ranges can be determined.

VIII. Hydrography: Susan Lozier (Duke University) and Fiamma Straneo (WHOI)

Four complete hydrographic occupations of the OSNAP East line will be conducted in collaboration with our international partners (Table 1). The purpose of these cruises, apart from providing servicing opportunities for the moored arrays, is twofold. First, they will provide "snapshot" ground-truth data for the moored arrays, including well-resolved boundary current transports and interior property fields that can be used to verify the accuracy of the overall AMOC reconstruction and property fluxes derived from the OSNAP array. Second, they will provide nutrient measurements that are highly useful in quantifying the NASPG circulation. For example, ISOW can be clearly identified by its low silicate concentration in the Iceland Basin. Standard parameters to be measured on each cruise are temperature, salinity, dissolved oxygen, nutrients, and shipboard ADCP and lowered-ADCP velocity profiles. Each of the sections will be conducted to WOCE standards, with ≤30 nmi spacing away from the boundaries and higher sampling in the boundary current regions and over the flanks of the Reykjanes Ridge. The first cruise in 2014, to be led by the UK, already has plans for additional biogeochemical sampling (including full carbon chemistry), and we will encourage similar activities on the US-led cruise in 2018 as part of an effort to integrate OSNAP with related biogeochemical programs.

IX. OSNAP integration: Susan Lozier (Duke University) and Bill Johns (University of Miami)

The overarching goal of the OSNAP program is to estimate the total meridional overturning and the integrated heat and freshwater transports in the NASPG. Thus, the success of this program hinges on the integration of all OSNAP array measurements, national and international. Plans to accomplish this goal are described in this section.

Proposed work prior to OSNAP data availability: The successful use of data from the RAPID/MOCHA (Kanzow et al. 2007) and ARGO (Willis 2010) arrays for AMOC estimates suggests the possibility of obtaining estimates at other locations with existing data. Initial results pairing the Line W array (Joyce et al. 2005) and the RAPID/MOCHA moorings on the Mid-Atlantic Ridge and off the African coast arrays is promising (Johanna Baehr, personal communication and Fischer, 2010). In collaboration with Baehr, we plan to test other combinations such as the 53°N Labrador Sea (Fischer et al. 2004) and Cape

Farewell (Bacon and Saunders 2010) boundary arrays, in conjunction with ARGO and altimeter data. Calculation of additional North Atlantic overturning measures will set the spatial and temporal context for the OSNAP observations and will also aid efforts to refine the methods that will be used to synthesize the OSNAP measurements into a single measure of the overturning.

OSNAP calculations: Once data from the OSNAP observing system are available, we will calculate basin-width integrated overturning, net heat, and net freshwater fluxes for OSNAP East and West separately, and combined. The expertise developed while computing overturning measures from OSSE simulations and existing data will guide our choices in how to include additional information, such as satellite and ARGO data, in the calculation of fluxes. Additionally, we will continue to use OSSEs as a test of our methodology. Linking overturning to deep water mass variability will be as discussed in section III.C, while linkages to wind and buoyancy forcing in the eastern NASPG will be assessed using a number of reanalysis products.

AMOC connectivity: The overturning, net heat fluxes, and net freshwater fluxes quantified by OSNAP in the NASPG will be compared to measures from other programs and latitudes; including OVIDE (Lherminer et al. 2010), RAPID (Cunningham et al. 2007), ARGO (Willis 2010) and THOR/NACLIM; and also to modeling estimates. In these comparisons, we seek to verify the meridional transmission of the AMOC signal as well as determine whether these measurements are consistent in the mean.

OSNAP optimization: An important goal of this proposed work is to assess the critical measurements needed for a long-term, cost effective AMOC observing system. Thus, we propose to analyze OSNAP observations to determine which measurements are critical for the determination of basin-wide integrated fluxes across the OSNAP lines. This assessment will incorporate ancillary data (e.g., ARGO and satellite) in the design of an optimally efficient long-term AMOC monitoring system.

OSNAP organization: A main organizational effort will be the management of international and national data acquired as part of OSNAP, a US responsibility. Please see Supplementary Material for the description of the OSNAP data management plan. The US will establish an OSNAP steering committee, with invitations to our international project partners. In addition to the steering committee functions mentioned in Section III.D, this committee will also coordinate research studies, including student projects. The proposed OSNAP meeting schedule (see Lozier's budget justification) is intended to facilitate coordination and communication.

X. Results from Prior Support

M. Susan Lozier (Duke University) and Amy S. Bower (WHOI)

Collaborative Research: Export Pathways from the Subpolar North Atlantic: Phase Two.

OCE 0824706; $231,810 (Duke) & OCE 0824652; $406,054 (WHOI); 9/1/08-8/31/11
**Publications to date from this grant:* Bower et al. (2009, 2011, 2012); Lozier (2010, 2012); Lozier et al. (2010, 2012); Gary et al. (2011, 2012); Rypina et al. (2011); Burkholder and Lozier (2011a,b)

Bill Johns and Lisa Beal (University of Miami); Molly Baringer and Chris Meinen (NOAA/AMOL)

An Observing System for the Meridional Overturning Circulation and Ocean Heat Transport in the Subtropical Atlantic: Extension of the RAPID-MOCHA Program.

OCE 0728108; $3,705,308; 01/15/08–01/14/14
**Publications to date from this grant:* Kanzow et al. (2009, 2010); Johns et al. (2011), Chidichimo et al. (2010), Rayner et al. (2011), van Sebille et al. (2011, 2012)

Fiamma Straneo and Steven Lentz (WHOI)

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

OCE 0751554; $888,809; 4/2008-3/2012
**Publications to date from this grant*: Straneo et al. (2010, 2011); Déry et al. (2011); St. Laurent et al. (2011, 2012); Sutherland et al. (2011)

* Full citations are listed in References.

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