Shelf/Slope Processes: Science Opportunities and Issues Relating to the OOI Pioneer Array

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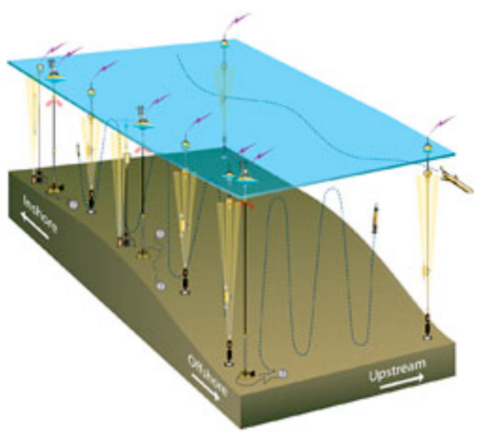

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I. Executive Summary

A workshop was held in Providence, Rhode Island, in February, 2011 to discuss science opportunities and issues relating to the Ocean Observatories Initiative (OOI) Pioneer Array. This process-oriented observatory will be located south of New England in a region well-suited for study of shelfbreak exchange processes due to the isolation from estuarine outflows, relatively weak tides, and the absence of complex bathymetry such as canyons. The Pioneer Array will be commissioned in January, 2014 and maintained for five years. The array design includes both moorings and autonomous mobile systems (gliders and powered vehicles). The primary goal of the workshop was to define broad science themes applicable to the observatory, and discuss whether the present design could be improved by some minor changes to better address the science themes.

The primary science goal for the Pioneer Array is the understanding of shelfbreak exchange processes and their relation to synoptic, seasonal, and inter-annual forcing. Four core science themes were the primary focus of workshop discussion:

1. Nutrient and carbon cycling over the outer continental shelf and upper continental slope;
2. Abundance, distribution, and biodiversity of phytoplankton near the shelfbreak;
3. Controls on the abundance and distribution of marine organisms at higher trophic levels;
4. Extreme events including winter storms and hurricanes.

It was also recognized that additional science topics can be addressed, one example being surficial geological processes. Since the Pioneer Array will be located in the "Mud Patch", a depositional area which is supplied by marine sediments from upstream, there will also be opportunities for investigation of sediment transport and how this relates to the impact of extreme events and influences the cycling of nutrients and carbon between the sediments and water column.

Regarding the observatory design, workshop participants thought that the overall design was sound and would address the science themes as well as provide opportunities for significant advancements in a number of areas of research. The primary recommendation was to shift some mooring locations further shoreward to reach the mean position of the foot of the shelfbreak front. The recommended design spans the 95 m to 480 m isobaths, with three moorings more closely spaced near the mean position of the shelfbreak jet. Two other notable recommendations were to modify nutrient sensor payloads on the Autonomous Underwater Vehicles (AUVs) to obtain more spatial and temporal coverage and to add pH sensors to mooring packages that measure pCO_2 in order to better resolve the inorganic carbon system.

The use of the mobile assets is an important component of the observatory. Three major priorities for gliders were defined at the workshop: 1) repeated cross-shelf lines upstream of the Pioneer Array to provide upstream boundary conditions for regional numerical models, 2) repeated along-shelf lines down the mean position of the core of the shelfbreak jet to provide information on frontal meandering, and 3) the resolution of important dynamical features such as warm-core rings and streamers of shelf water over the upper slope adjacent to the mooring array.

Based on salinity/nutrient relationships, information from the glider aligned with the axis of the shelfbreak jet could also contribute to estimates of nutrient fluxes between the upper slope and offshore edge of the shelfbreak front. Recommendations for AUV sampling emphasized repeat missions. It was suggested that one vehicle conduct repeated cross-shelf transects along both the mooring line and another line near the flanking moorings to obtain high-resolution hydrographic and nutrient data across the front. The other vehicle could do along-shelf lines both at the mean position of the foot of the shelfbreak front as well as an adjacent section further onshore to determine eddy fluxes of nutrients between the frontal region and the shelf. This AUV mission scheme would provide weekly resolution of both cross-shelf and along-shelf variability of the shelfbreak front.

Enhancements to the Pioneer Array were discussed at length. Process cruises were seen as an absolutely vital element of Pioneer Array science. The necessity of measuring biological and bio-geochemical rates requires a robust suite of process cruises. It was also recommended that systematic sampling for calibration of sensors on moored profilers and moorings occur at the turn-around cruises. Even if this requires additional ship time, the need for the maximum cross-calibration to ensure high quality real-time data makes this a high priority. Other key enhancements would be to enable measurements of fluxes and rates at the sediment/water-column interface and resolve the bottom boundary layer. These could include deployment of additional moorings or independent bottom landers, as well as incorporating near-bed sensors into the array moorings. Other possible enhancements include establishing bistatic High-Frequency radar systems to extend surface current mapping across the Pioneer Array region and deployment of passive acoustics to characterize marine mammal activity.

The science-operational interface was discussed at length. Important issues include the prioritization of resources and establishing mechanisms to ensure that input from the scientific community is part of the operational framework for the Pioneer Array. A number of specific issues are listed in Section VII of this report, with the recognition that guidelines for science-operational interactions -are under development within the OOI program and thus many issues cannot be fully addressed at this time.

The Pioneer Array was also considered within the larger regional setting. Numerous efforts in regional modeling are under way that can be leveraged, including systems being developed by regional associations for ocean observing. Similarly, a number of agencies have either done studies in the area in the past or are continuing efforts in areas such as remote sensing. A number of recommended interactions with both the regional associations and other agencies with science programs and interests in the area arenoted.

The workshop led to direct, constructive engagement between representatives of the science community and the OOI team. A number of concrete recommendations were made which have been directed to the OOI leadership team. The potential for ground-breaking science was highlighted by a number of participants covering a wide range of sub-disciplines with the ocean sciences. Hopefully, the experience from this workshop will also serve as a guide for future OOI science workshops.

II. Introduction

The Mid-Atlantic Bight Pioneer Array

The Pioneer Array is a process-oriented observatory that is being established on the continental shelf and slope of the Mid-Atlantic Bight (MAB) south of New England (Figure 1) as part of the National Science Foundation (NSF) Ocean Observatories Initiative (OOI). A brief history of the OOI program development and the Pioneer Array concept is provided in the Background (Section III, below) along with a summary of key OOI documents relating to Pioneer Array design and broad science themes the observatory will address. At the time of the Providence workshop in February 2011, the Pioneer Array was in the early construction phase, with transition to operational status targeted in early 2014. Following a 5-year deployment, it is intended that the array will be relocated to another coastal ocean setting, to be selected through a science review process.

The MAB Pioneer Array will collect multi-scale, real-time oceanographic data in a complex and biologically productive shelf break setting, providing the capacity for state-of-the-art process studies of nutrient and carbon cycling in a well-resolved physical environment. The Pioneer Array location was selected with the intention that the observations will have relevance to shelf/slope interactions globally, as well as for study of MAB-specific processes. The location for the observatory, south of New England, was chosen to focus on shelfbreak exchange processes without further complicating factors such as Gulf Stream proximity, estuarine outflows, complex bathymetry, or strong tides. The Pioneer Array will also provide advances in capacity to investigate air-sea-wave interactions and gas transfer (in real time) in a region that experiences extreme meteorological forcing events (ranging from winter snow storms to hurricanes). Such events can have significant societal and economic impact, and observations under extreme conditions could contribute to improved forecasting systems for severe marine weather and storm-associated hazards.

A range of modern technologies will be part of the Pioneer Array, advancing the state-of-the-art in marine sciences in a number of areas. To provide the capacity to quantify property exchange and heat, salt, and nutrient fluxes between the shelf and slope, the observatory will combine several advanced moored instrument systems with a mixed fleet of mobile assets. The latter will include both self-propelled Autonomous Underwater Vehicles (AUVs) for short-term (~1 day) missions and autonomous gliders for extended missions (2-3 months). The use of the mobile assets as a core component of the observatory will also provide opportunities to develop and refine adaptive sampling techniques that will contribute to more accurate numerical modeling and forecasting.

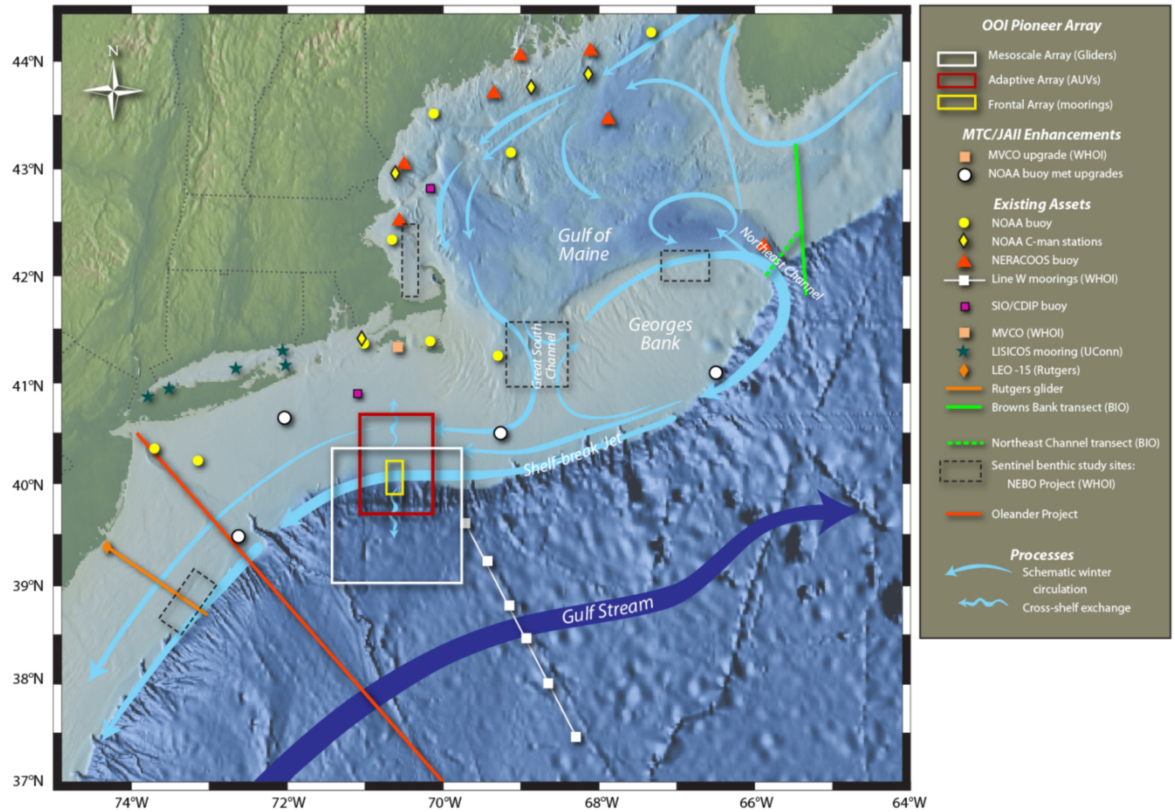

Figure 1: A schematic diagram of the Middle Atlantic Bight and Gulf of Maine showing the Pioneer Array at the shelfbreak south of New England. Arrows denote the mean circulation in the region, and assets within the region are denoted by symbols identified in the column on the right hand side. Figure courtesy of A. Plueddemann.

Science Opportunities

The Pioneer Array will provide unique capabilities to address a wide range of science questions. A number of over-riding science themes are discussed in Section IV. A few broad points are worth stating at the beginning. First, the Pioneer Array is intended to provide opportunities for individual investigators (along with students or post-doctoral researchers) as well as research teams from multiple institutions, both through use of the core observatory infrastructure and through projects that augment the array. Potential research projects using the Pioneer Array could range from field trials of new sensors to inter-disciplinary process studies, including comparisons with other shelfbreak regimes. Because data will be provided in near-real time over the internet, researchers will be able to analyze and assimilate data to address particular science problems from their home institutions and other remote locations. Second, the near-real time data can also be used to guide specific feature-oriented process studies using ships or additional vehicles supplemental to the core infrastructure and sensors of the Pioneer Array. This means, for example, that the exact location and along-shelf scale of a streamer of shelf water flowing onto the continental shelf could be pin-pointed so that the streamer could be sampled continuously over several weeks to see it evolve over time. Third, the combination of multi-function nodes at the bottom and profilers which cover the entire water column allows study of interactions such as bio-geochemical cycling between the sediments and overlying (and constantly changing) water masses which have not been possible before. We fully anticipate that new combinations of researchers will be engaged in using the Pioneer Array to address the complicated nature of shelf and slope variability and its relation to larger scale forcing.

The Pioneer Array will consist of a core infrastructure with a suite of sensors (Table 1) that will be deployed for five years. In addition, it is expected that process-oriented cruises will be conducted to study in more detail specific issues such as larval transport, vertical mixing processes, or genetic diversity of organisms in the shelfbreak front versus the shelf and slope. By providing power generation at offshore mooring sites over an extended period of time, there will be unprecedented opportunities to study the frequency and scales of shelfbreak exchange processes and to test and apply new sensors to this complex oceanographic environment. The novel application of both gliders to resolve slope features and AUVs equipped with nutrient sensors will allow for high-resolution surveys throughout the year, including extreme events such as winter storms and hurricanes where it is not safe to collect scientific data from a ship. The Pioneer Array will also provide a test bed for developing methodologies for autonomous vehicle use in regions of large spatial gradients and temporal variability. Furthermore, the use of data-assimilative models will provide state-of-the-art three-dimensional, time-dependent simulations that will address fundamental questions regarding the nature of exchange of heat, salt, and nutrients between the shelf and slope and the role of this exchange in ecosystem dynamics.

Site	Bulk Met	DCFS	Surface Wave Spectra	CTD	pCO2	pH	DO	Nitrate	Fluoro (3 chan)	Optical Absorp/ Atten	Spectral Irrad	PAR	Seafloor Press	Point Velocity	3-D Point Velocity	ADCP	bio-acoustics
Pioneer Inshore	buoy	buoy		5 m MFN	buoy MFN	5 m MFN	5 m MFN	5 m	5 m	5 m MFN	5 m		MFN	5 m MFN			MFN
Pioneer Central	buoy	buoy	buoy	5 m MFN	buoy MFN	5 m	5 m MFN	5 m	5 m	5 m MFN	5 m		MFN	5 m MFN			MFN
Pioneer Offshore	buoy	buoy		5 m MFN	buoy MFN	5 m	5 m MFN	5 m	5 m	5 m MFN	5 m		MFN	5 m MFN			MFN
Pioneer Central inshore				profiler			profiler		profiler			profiler			profiler	frame	
Pioneer Central offshore				profiler			profiler		profiler			profiler			profiler	frame	
Pioneer Offshore				profiler			profiler		profiler			profiler			profiler	frame	
Pioneer Upstream inshore				profiler			profiler		profiler			profiler			profiler	frame	
Pioneer Upstream offshore				profiler			profiler		profiler			profiler			profiler	frame	
Pioneer Inshore				profiler	profiler		profiler	profiler	profiler	profiler	profiler	profiler			profiler	frame	
Pioneer Central				profiler	profiler		profiler	profiler	profiler	profiler	profiler	profiler			profiler	frame	
Glider Ops Area				glider			glider		glider			glider				glider	
AUV Ops Area				AUV			AUV	AUV	AUV			AUV				AUV	

Table 1- The sensor types for the various moorings and vehicles for the Pioneer Array. MFN stands for multi-function node which will be located near the bottom. The sensor types are located on the first row of the table and the mooring/vehicle locations are located in the first column.

Motivation and Planning for the Providence Workshop

Given the significant technical and logistic challenges faced in the design and construction process, recent OOI documentation concerning the Pioneer Array has focused on the basic systems design and engineering. While this process has been guided by the overall science objectives for the OOI network, specific research applications for the Pioneer Array infrastructure have not been addressed in depth in the program documents. Thus, the organizers of the Providence workshop felt that it would be appropriate at this time to revisit the science opportunities that will be provided by the MAB Pioneer Array, and solicit community input into the final instrument configurations for moorings and mobile systems, the locations of moorings, and mission plans for mobile assets. With MAB observatory commissioning and initial full range of operations scheduled in 2014, it was also felt that a community review of system capabilities would be valuable and timely in terms of informing plans for science programs that will utilize the core infrastructure of the Pioneer Array (which could range from individual PI projects to larger collaborative programs), and to identify research areas where augmentation of the array will be required.

In planning for the workshop, 30 to 40 participants was targeted as an effective size for focused discussion of Pioneer Array capabilities and science applications. Given the limited size of the workshop, it was decided that interested academic or research institution would be asked to select one participant who would represent research interests of institutional colleagues. After a first round of responses, a limited number of individuals were contacted to balance disciplinary, regional, and institutional representation. The workshop was announced at the Middle Atlantic Bight Physical Oceanography and Meteorology workshop at the Stevens Institute of Technology in October, 2010 as well as at a Town Hall meeting at the American Geophysical Union Fall meeting in San Francisco in December, 2010. A website for the workshop was set up a month prior to the workshop with information including logistics, background documents and papers, and a list of attendees (*https://sites.google.com/site/pioneerarrayscienceworkshop/*). Two-page statements of interest were also solicited from interested parties whose schedule precluded their attendance at the workshop. These statements were used to help develop the agenda for the workshop and to inform workshop discussions.

Workshop Discussions

The science workshop was held in Providence, RI from February 22-24, 2011. There were 26 participants from 20 institutions at the workshop (two others were prevented by travel difficulties from participating) along with representatives from OOI, NSF, and the Consortium for Ocean Leadership (COL). Workshop participants and affiliations are listed in Appendix A and the workshop agenda appears in Appendix B. Following an introduction to the broad science themes that have motivated the MAB Pioneer Array design by the workshop organizers, NSF and OOI personnel briefed the workshop participants on the status of the OOI program, the basic array configuration (platforms and measurements), capabilities (mechanical, power, communications) and the OOI data management system. The workshop attendees from the science community were then tasked with defining core Pioneer Array capabilities and highlighting opportunities where augmentation of the array or complementary process studies would expand the breadth of science themes capable of being addressed by the observatory.

It was recognized that a number of important areas impacting prospective science users of the Pioneer Array infrastructure were still under development, including proposal guidelines, Operations and Maintenance (O&M) plans, and the OOI data management plan. Thus, workshop discussion of these issues was in fairly broad terms. It is expected that more detailed guidance and documentation of these issues and other aspects of the science-operational interface (i.e., how science users will interact with the OOI operators of the Pioneer Array) will be defined by NSF and OOI in the near future. The workshop discussion also included consideration of what background information is needed to allow potential Principal Investigators to prepare competitive science proposals for the NSF core panels. Note that the core ocean science panels in NSF are the mechanism through which Pioneer Array (and OOI) science proposals will be funded. There are presently no plans for dedicated OOI science funds or OOI-exclusive science panels.

White Paper

The present document is intended to inform potential science users of the capabilities of the present design of the MAB Pioneer Array and highlight opportunities for the scope of research that may be addressed through this network. As described below, the core capabilities of the Pioneer Array could provide the foundation for a wide range of specific research projects. It is envisioned that complementary investigations will range from focused single-investigator projects to multi-disciplinary, multi-investigator collaborative efforts. Potential studies could include comparisons to shelf/shelfbreak processes in other ocean margin systems as well as investigations focusing on MAB-specific topics.

The outline of the white paper is as follows: Background for the OOI program and Pioneer Array appears in Section III. Core science themes are presented in Section IV. The Pioneer Array design is described in Section V, while Section VI discusses enhancements to the core Pioneer Array design necessary for addressing various science themes, such as focused process cruises. Issues pertaining to the Science-Operational Interface are covered in Section VII, and the broader regional and temporal context for Pioneer Array science is summarized in Section VIII. Finally, a summary of workshop conclusions and recommendations appears in Section IX.

III. BACKGROUND

Ocean Observatories Initiative

The Ocean Observatories Initiative (OOI) is a major research infrastructure project of the NSF Division of Ocean Sciences (NSF OCE). Following a 5-year construction program, a 25-30 year science program is envisioned. The OOI is intended to provide new, transformative capabilities for ocean research and is an NSF contribution to global and national ocean observing networks (*http://www.oceanobservatories.org/*). (A number of planning and implementation documents that are referenced below are available through: *http://www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/documents-and-publications/*). The basic scientific rationale for OOI is developed in the OOI Science Prospectus (October 2007) which identifies several major science themes to be addressed by the network. Additional science questions under the major themes and how these guide the conceptual design for different components of the OOI are defined in a set of "traceability matrices" (see Appendix A-10 for "Coastal Ocean Dynamics and Ecosystems – Shelf/Slope Exchange Processes").

The observing components for the initial phase of the OOI are: the **Global Observatory**, a set of moored systems to be deployed at high latitude locations as sentinels for climate change; the **Regional Observatory**, a cabled seafloor geophysical observatory on the Juan de Fuca Plate and adjacent shelf and slope region off the Pacific Northwest; and the **Coastal Observatory**, located in two coastal ocean/shelf systems. The Coastal Observatory consists of the **Endurance Array**, a cabled long-term network off Oregon, and the **Pioneer Array**, a relocatable array of moored and mobile observing assets to be deployed and operated for five years at the shelf break of the Middle Atlantic Bight south of Cape Cod. The OOI **Cyberinfrastructure** component will provide communications and data management services across the observing components and will establish and operate the data access system for end users of OOI data and products. The OOI Education/Public Engagement component will focus on educational and outreach infrastructure to enable activities leveraging the science from the OOI observatories.

For the present document, it is important to recognize that the MAB Pioneer Array is one of several parallel tracks of infrastructure development for the OOI. This has influenced both the array design (e.g., a number of key system components are common to both the Pioneer Array and Endurance Array) and how science users will interface with the system (through the overall Cyberinfrastructure network). It is also important to recognize that the original conceptual designs for the Pioneer Array and other elements of the OOI were modified through several rounds of systems engineering and fiscal reviews (below).

The Pioneer Array Concept

The central objective for the initial deployment of the Pioneer Array is to obtain a sustained multi-scale, three-dimensional view of physical, biological and biogeochemical interactions at the MAB shelf break. To provide this, a multiplatform array combining moored and mobile assets with high spatial and temporal resolution will be deployed, spanning the outer continental shelf to upper slope south of New England. The Pioneer Array concept developed over several years, starting with a community workshop organized through the NSF Coastal Ocean Processes program (CoOP) in the spring of 2002 (Jahnke et al. 2002). The CoOP workshop addressed how coastal ocean research could be advanced through observing system technologies and how coastal ocean observatories might be configured to optimize observations at key time and space scales for various processes. A widely distributed set of long-term observations (decades) was envisioned as part of the coastal network (the "Endurance" component). The Pioneer Array was proposed as a multi-platform system that could be deployed at targeted locations for several years for studies of specific processes, and then relocated to another study site. With deployments of over several years in duration, a range of conditions would be observed with high resolution, including examples of episodic events that can only be captured through time-series observations.

The Pioneer Array concept was further developed in subsequent community workshops, including a CoOP-sponsored workshop in 2003 (Jahnke et al. 2003). A number of candidate studies for the Pioneer Array were proposed in this workshop report, including a focus on shelf/slope exchange processes in the MAB. Given the variable location of the shelfbreak front and associated jet, and the influence by warm core rings, frontal instabilities, intrusions and varied wind forcing on exchange at the shelf margin, it was proposed that a multi-platform array, deployed for a period of 3-5 years would be required to address this topic. It was argued that the greatest scientific impact for the array across a range of disciplines would be obtained by combining moored instruments with autonomous mobile systems (AUVs and gliders).

At the time of the CoOP workshops in 2002 and 2003, it was recognized that the sensors available for sustained deployments in coastal and shelf settings were predominantly for physical variables. Although new options for chemical and biological sensors were emerging, it was concluded that directed sampling programs would be needed to supplement the array observations, particularly for studies of many biological and biogeochemical processes. While new sensors have been introduced in recent years, and there have been advances in the effectiveness of integrated anti-fouling systems for a number of optical and chemical sensors, the need for supplemental sampling remains for many research areas (see Section VI of this report).

Development of the Pioneer Array under OOI

The OOI Project Office was established by NSF OCE in 2004 (the history of the program is summarized at: *http://www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/planning-and-history/*). With input from the community through a Request for Assistance (RFA) process, OOI Project Office along with external science and technical advisory committees produced an initial Conceptual Network Design (CND) that was presented at the OOI Design and Implementation Workshop in Salt Lake City in March 2006. This was followed by a Conceptual Design Review by NSF in 2006 and generation of a revised CND in consideration of design refinements and updated cost estimates. The major consortium partners for the OOI construction were selected in 2007. The OOI Program Management Office established within the Consortium for Ocean Leadership (COL; *http://www.oceanleadership.org/*). The MAB Pioneer Array is a component of the Coastal Node, with the Woods Hole Oceanographic Institution being the lead implementing organization. Initiation of the construction process by the implementing organizations proceeded through Preliminary Network Design (PND) and Preliminary Design Review (PDR) stages, and a Final Design Review (FDR) by the National Sciences Board, which recommended in July 2010 that OOI proceed with construction.

The Final Network Design for the OOI (FND; updated in April, 2010), includes the basic platform and package configuration for the MAB Pioneer Array. The FND provided the starting point for discussion of Pioneer Array capabilities at the present workshop. It should be noted that while variables to be measured and target capabilities were specified in the FND, specific instruments and packages were not defined by OOI at the time of the Providence workshop due to the fact that the contract award process had not been completed. Also, the FND was primarily an engineering prospectus and did not discuss science objectives of the Pioneer Array in any detail.

OOI Data Policy and Data Management Structure

The guiding principles for the OOI data policy and data management are free and open access to high quality data and data products as rapidly as possible. Much of the data is intended to be available in near real-time (with latencies as short as technically feasible). Data management is the responsibility of COL. Data policy is proposed to NSF and reviewed by external panels. PIs may request exclusive access to data associated with their projects for up to one year (decisions made on a case-by-case basis) after which all data will be publicly accessible through the CI.

At the time of the Providence Workshop, the OOI Data Management Plan (DMP) was at "candidate" status, with a proposed plan that would be further refined through community review and feedback. The candidate DMP was developed following review of data management systems from academia, government agencies and industry and adopted what were viewed as best practices. Many components of the candidate OOI DMP were based on the prior work of the NOAA Integrated Ocean Observing System (IOOS) Data Management and Communications (DMAC; documentation at: *http://www.ioos.gov/library/difdmacdocs.html*). Consistency with the IOOS DMAC will ensure interoperability with other regional and national observing efforts, and takes advantage of the considerable level of community effort that has gone into IOOS DMAC planning, including definition of data and metadata standards for ocean observing systems. Along with developing the user interface, the OOI CI will develop a user feedback process and incorporate these comments into ongoing development and refinement. The CI will also be responsible for the OOI data archive for observations, data products and associated metadata.

IV. Core Science Themes for the Pioneer Array

The primary science goal for the Pioneer Array is an improved understanding of cross-frontal exchange between the continental shelf and slope. The small temporal and spatial correlation scales within the shelfbreak front, (approximately 1 day and 10 km, Gawarkiewicz et al., 2004) makes this a very challenging problem, and necessitates a multi-scale approach in which motions over both the continental shelf and continental slope are resolved on appropriate space and time scales. While previous science programs such as the Shelf Edge Exchange Program (SEEP) and the Ocean Margins Program (OMP) provided insight into important exchange processes, the application of new technology, including AUVs and gliders as well as new biological and chemical sensors, allows for new approaches to sampling and modeling of shelfbreak exchange. By enabling well-resolved, real-time observations over an extended time period of five years, the Pioneer Array will provide unprecedented insight into the relative contributions of a number of different exchange processes as well as their impact on ecosystem dynamics, biogeochemical processes, and nutrient and carbon cycling.

In this section, we first review important shelfbreak exchange processes and the oceanographic and geological setting for the Pioneer Array area. This is followed by background for additional broad science themes that may be addressed through projects utilizing the core observatory infrastructure provided by the Pioneer Array. These potential research areas include: nitrogen and carbon cycling; phytoplankton production, distribution, and biodiversity/assemblages; extreme events, including storm response and air-sea interaction; and controls on distribution and abundance of zooplankton, fish, marine mammals, and other organisms from higher trophic levels.

Overview of Shelfbreak Exchange Processes

There are a number of important shelf/slope exchange processes within the MAB that have been identified. A few significant and recurring exchange processes include frontal instabilities and associated meandering and eddy fluxes (e.g. Lermusiaux, 1998; Lozier et al., 2002; Gawarkiewicz et al., 2004), warm core ring interactions with the shelfbreak front including streamer formation (e.g. Bisagni, 1983; Ramp et al., 1983; Gawarkiewicz et al., 2001; Joyce et al., 1992), response to wind forcing including both winter storms and hurricanes (e.g. Lentz et al., 2003a; MacKinnon and Gregg, 2002, 2005) and saline intrusions within the seasonal pycnocline (e.g. Boicourt and Hacker, 1976; Aikman and Posmentier, 1985; Lentz, 2003b). In addition, the general topics of both vertical mixing over the shelf and slope (e.g. Hales et al., 2010; Rehmann and Duda, 2000) as well as lateral mixing (e.g. Sundermeyer and Ledwell, 2001) are important to the dynamics of individual exchange processes. A schematic diagram illustrating many of these physical exchange processes appears in Figure 2.

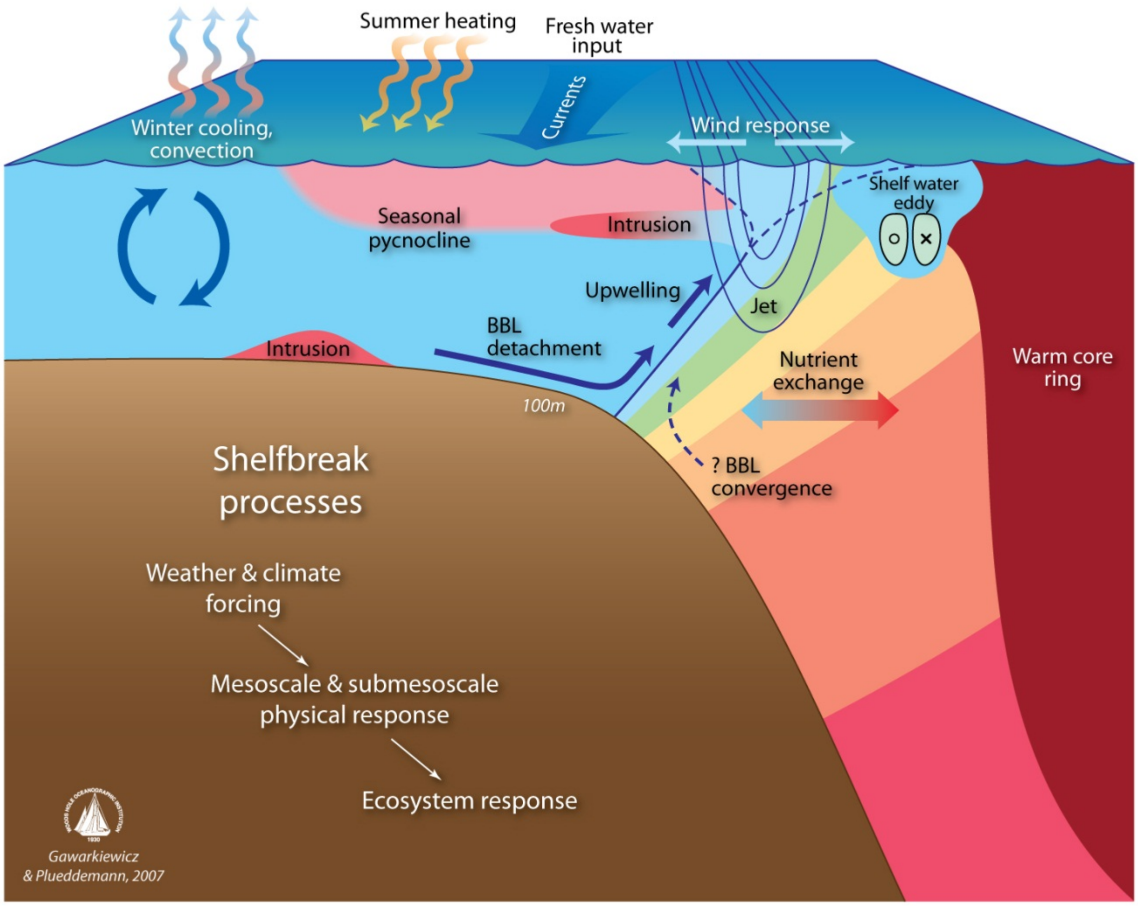

Figure 2: A schematic diagram showing important cross-shelf exchange processes across the shelfbreak in the Middle Atlantic Bight.

The shelfbreak frontal jet is relatively narrow (order 10-20 km- Linder and Gawarkiewicz, 1998; Fratantoni and Pickart, 2007) with mean velocities of roughly 25 cm/s and extreme velocities of up to 80 cm/s. This results in a fairly unstable front which is conducive to the generation of large amplitude meanders and detached eddies of shelf water. Frontal waves tend to have wavelengths in the range of 20 to 40 km and indications from a one-year moored array are that instabilities are more important in the spring and summer than in the winter when wind forcing is the dominant source of frontal variability (Houghton et al., 1988). Frontal meandering can lead to substantial cross-shelf displacements of the foot of the shelfbreak front; onshore displacements of 10-20 km in a few days are common. Flagg et al. (2006) show some dramatic examples of short term frontal variability off New Jersey using ADCP (Acoustic Doppler Current Profiler) data from the *M/V Oleander*.

Warm core rings are an important forcing mechanism for the shelfbreak front. Originating in the Gulf Stream, the rings tend to drift to the west until they encounter sloping topography. They continue to drift to the southwest until they eventually dissipate under the influence of friction or are re-absorbed into the Gulf Stream. When they are in close proximity to the shelfbreak front, the onshore flow on the western side of a warm core ring tends to steepen the shelfbreak front and increase the speed of the jet. This may lead to the development of frontal meanders to the southwest of the ring (Ramp et al., 1983). On the eastern side of the ring, flow is generally offshore and shelf water is carried offshore in the form of a streamer (e.g. Bisagni, 1983; Gawarkiewicz et al., 2001). There is substantial inter-annual variability in the number of warm core rings that form in a given year (Chaudhauri et al., 2009a,b), which may be an important factor in generating inter-annual variability of cross-shelf exchange at the shelfbreak. In addition to the asymmetry of flows on either side of the ring, there may also be onshore translations of the shelfbreak front of order 10-20 km (Gong, 2010).

Wind forcing is an important element of shelfbreak exchange. Lentz et al. (2003a) have shown that in upwelling favorable winds, offshore transport in the surface mixed layer is balanced by onshore flow near the bottom. The foot of the shelfbreak front migrates onshore during upwelling conditions (Castelao et al., 2008). Onshore excursions of the foot of the front and associated vertical mixing of bottom intrusions may be an important factor in generating onshore fluxes of nutrients from the continental slope to the continental shelf (Siedlecki et al., 2011).

Another important exchange process seasonally is the onshore intrusion of saline slope water (Lentz, 2003b). This tends to occur preferentially at the depth of maximum stratification, within the seasonal pycnocline. However, both near surface and near-bottom saline intrusions have also been identified in the historical record. The near-surface and near-bottom intrusions are likely to be forced by both wind-driven motion as well as frontal meandering.

Vertical mixing processes play an important role in determining both the evolution of the stratification within the front as well as affecting the cross-shelf exchange processes. There are many implications of vertical mixing processes, but two examples include the impact of internal wave motions on vertical heat fluxes within the shelfbreak front and over the continental shelf (Shroyer et al., 2010) as well as the impact of vertical mixing on the primary productivity within the front (Hales et al., 2010). Further work is necessary to establish the contributions of vertical mixing processes to the temporal evolution of the major cross-shelf exchange processes mentioned previously.

A key element of cross-shelf flow within the shelfbreak front is transport of buoyancy within the bottom boundary layer and associated upwelling. This was originally identified by Gawarkiewicz and Chapman (1992) in an idealized numerical model study, and was then observed within the front using a near-bottom dye release by Houghton and Visbeck (1998). Further studies have identified upwelling rates using neutrally buoyant floats (Barth et al., 2004), analysis of temperature changes along frontal isopycnals (Pickart, 2000; Linder et al., 2004), a suite of dye releases (Houghton et al., 2006), as well as long-term numerical model simulations of the front (Chen and He, 2010). A theoretical treatment of the mechanism of buoyancy transport in the bottom boundary layer and its role in frontogenesis at the shelfbreak appears in Benthuysen (2010). Vertical velocities have been measured in the range of roughly 5-20 m/day, and offer the potential for transporting nutrients from the near bottom over the edge of the shelf into the euphotic zone. In general, both the surface and bottom boundary layers are expected to be important factors in the dynamics of cross-shelf exchange processes.

There are also important annual and inter-annual signals that affect both the cross-shelf position of the shelfbreak surface thermal signature (Bisagni et al., 2006, 2009) as well as the composition of the water masses of the continental shelf (Mountain, 2003). This will be discussed further in section VIII.

Geological Setting and Questions in Surficial Geology

The Pioneer Array will be deployed in a region of anomalously fine-grained seafloor known colloquially as the "mud patch" (Figure 3; Twichell et al., 1981; Bothner et al., 1981). These sediments cover an area approximately 170 km by 74 km, located in water depths between 60 m and 150 m (Bothner et al., 1981), and are up to 13 m thick resting on an undulating transgressive sand sheet (Twichell et al., 1981). The mud patch is a region of modern shelf accumulation (Bothner et al., 1981), a rare condition on the US continental shelf which is otherwise primarily non-depositional in the modern setting (Swift et al., 1972), and often erosional (Goff et al., 2005). The primary working hypothesis for the origin of the mud patch is that these sediments are derived by storm and/or tidal erosion of Nantucket Shoals and Georges Bank, transported westward by the mean drift, and then deposited off Southern New England due to more quiescent tidal conditions (Twichell et al., 1981). Limited tidal current measurements support this hypothesis (Twichell et al., 1981).

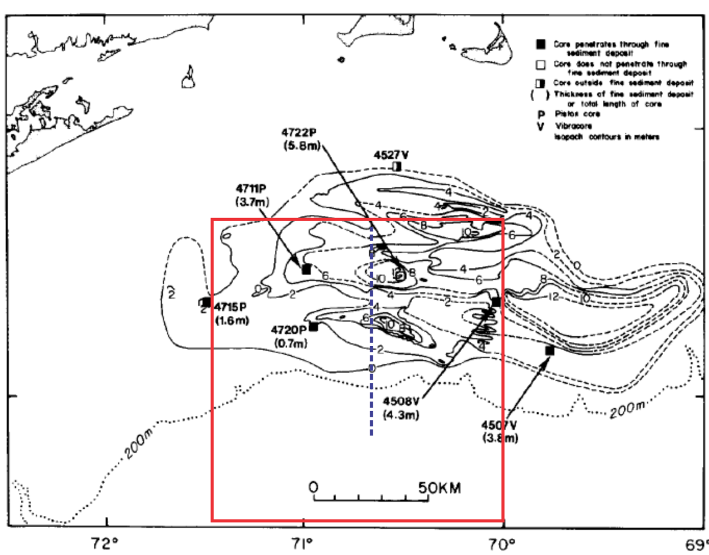

Figure 3. Isopach map of the southern New England shelf "mud patch" (Twichell et al., 1981), with likely position of the Pioneer Array (blue dashed lines) and overall area of interest for the Array (red box), including planned glider and AUV coverage. Maximum recorded thickness within the mud patch is 13 m; this occurs beneath the middle-outer shelf.

With regard to the Pioneer Array and the physical oceanographic issues motivating its installation, a salient fact about the Southern New England mud patch is that it is not derived from terrestrial inputs; rather, it is derived almost entirely from remobilization and re-deposition of continental shelf sediments by storms and tides. Here, the regional seabed geology and the regional physical oceanography are a *strongly coupled system*, so that studies of patterns of erosion and deposition, sediment transport and bottom geomorphology, should provide important evidence for physical oceanographic conditions spanning short to long time scales. Regional marine geological and geophysical research of the seabed can be conducted to investigate the sedimentary dynamics associated with formation of the mud patch, and to link these studies to the physical oceanography work associated with the Array.

From a geological perspective, there are several motivations for further work associated with understanding the dynamic sedimentary environment of the outer shelf and upper slope (to depths of ~1300 m). Modern erosion on the outer shelf, for example, was recognized in earlier studies of the New Jersey shelf (Goff et al., 2005), but these locations were not linked to consequent deposition, nor were they adequately linked to physical oceanography studies that could explain the amount of erosion observed. Studies of the southern New England shelf linked to the Pioneer Array research could answer fundamental questions about these sedimentary processes. For example, what is the average residence time of surficial fine-grained sediments and particle-hosted particulate organic carbon (POC) now associated with the "mud patch"? This could be studied using shallow-to-deep coring, followed by stratigraphic examination to identify event layers of reworking extent and frequency, and short (e.g., ^{234}Th, ^{7}Be) and medium (^{210}Pb and ^{137}Cs) half-life geochronologies of cored sediments, to examine (1) seasonal to inter-annual variability in depositional flux, (2) effect of bioturbation on downmixing of fines, and (3) spatial variability in burial rates of POC and mineral particulates. Core data would be extrapolated to the full Pioneer Array area of interest utilizing very high-resolution seismic surveys of the mud patch. The preservation of sand bodies on the shelf is also an important consideration as modern analogs for hydrocarbon-bearing reservoir rocks. The New Jersey studies suggests that long-term exposure of sand bodies to non-depositional conditions, as occurs on most of the US Atlantic shelf, can lead to significant reworking and degradation of the sand body, so much so that there is little of it left on the outer shelf (Goff et al., 2005). The mud patch, however, demonstrates how sediment bodies on the mid-shelf (and potentially in deeper water) can be well preserved, even on shelves where there are no significant net sedimentary inputs to the system. The Array covers the upper continental slope, near the heads of several slope canyon systems. Questions there could be posed regarding the exchange of particulate matter across the shelfbreak, the initiation of slope mass flows, and possible connections of these to the shelfbreak jet, storms, internal waves or other oceanographic forcing.

The last published survey of the southern New England mud patch was conducted in 1978 (Twichell et al., 1981). Advances since then in survey equipment, interpretation software, and coring technology (e.g., Nittrouer et al., 2007) make the region ripe for new work. Multi-beam bathymetry and backscatter can be used to map the seafloor morphology and sedimentary texture of the region in great detail. CHIRP acoustic reflection can be used to map the shallow subsurface (to ~30 m penetration) at very high resolution. Sophisticated interpretation software can be used to render seafloor and sub-seafloor surfaces in 3D. New long piston-coring systems should easily penetrate the full thickness of the mud patch. These new technologies should allow us to greatly advance our morphological and geological understanding of the region.

Biogeochemical Processes on Continental Margins

There is a pressing need to better understand biogeochemical cycling in continental margins as such systems are exposed to both local (e.g., excess nutrient loading) and global (e.g., warming water temperature & ocean acidification) human impacts. There is already evidence that such impacts have altered how marine systems function. For example, Boyce et al. (2010) recently reported significant climate induced declines in ocean phytoplankton biomass, Diaz and Rosenberg (2008) reported widespread increases in hypoxic/anoxic coastal shelf regions due to cultural eutrophication, and warming water temperatures has lead to decreases in benthic metabolism and major seasonal shifts in nitrogen cycling in a New England estuary (Fulweiler et al. 2007, Fulweiler and Nixon 2009, Fulweiler et al. 2010).

While continental margins are probably best known for supporting productive fishing grounds, they also provide a less well-constrained, but important ecosystem service. That is, they receive and process anthropogenic nutrients thus decreasing human impacts on the ocean (Liu et al. 2010). These borderlands between the terrestrial environment and open ocean are considered to be "hot spots" for biogeochemical cycling in general and for nitrogen cycling in particular (Christensen, 1994; Christensen et al., 1987; Codispoti et al., 2001). However, there are surprisingly few actual measurements of water column and sediment processes in continental shelf regions, and those that are available are typically limited both spatially and temporally. Much of our current understanding of shelf/margin biogeochemistry is thus based on incomplete observations and models that are extrapolated to wider geographic and seasonal scales (Seitzinger and Giblin, 1996; Fennel et al., 2009).

The Pioneer Array will provide an unprecedented opportunity to couple biogeochemical measurements with high resolution data on exchange between the continental shelf and slope within the Mid-Atlantic Bight (MAB), making it possible to link both water column and sediment carbon and nutrient cycling to the dynamic physical nature of this environment. With an improved understanding how these processes change in space and time, it will be possible to base further development of coupled physical-biogeochemical models on empirical data; models that can be used and tested in continental margins worldwide.

Continental Shelf Nitrogen Cycling

The tight coupling between the carbon and nitrogen cycle has important implications for ocean primary productivity and ultimately atmospheric CO_2 levels (Falkowski 1997; Falkowski et al. 1998; Gruber and Galloway 2008). Since most marine waters are considered to be nitrogen (N) limited any additional source of N would increase primary production and presumably increase carbon deposition to the deep sea. A major factor controlling N limitation in marine systems is the balance of two N cycle processes, denitrification and nitrogen fixation (Codispoti 2007; Howarth et al. 1988b). Denitrification converts nitrate (NO_3^-) into dinitrogen (N_2) gas, thus removing it from the labile N pool for most organisms. In marine systems, most denitrification is thought to take place in sediments that are rich in organic matter and anaerobic within the top few mm. A schematic diagram of nitrogen cycling in continental shelf sediments appears in Figure 4. Denitrification occurs through two main pathways in sediments: 1) direct denitrification, where nitrate diffuses from the overlying water into the sediments or 2) coupled nitrification-denitrification, where ammonia released during the decomposition of organic matter is nitrified in a two-step bacterial mediated oxidation process to nitrate and that nitrate fuels denitrification. Typically, we assume that most of the denitrification is coupled to nitrification.

Denitrification in continental shelf sediments is thought to remove upwards of 50% of the total nitrogen input to the oceans (Seitzinger and Giblin, 1996).

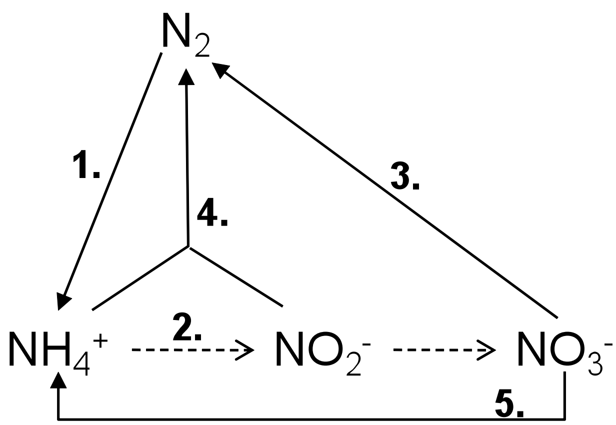

Figure 4. Diagram of important N cycling processes in marine sediments: 1) N fixation: transformation of dinitrogen (N_2) gas to ammonium; 2) nitrification: the two-step oxidation of ammonium to nitrite (NO_2^-) and then to nitrate (NO_3^-), this is an aerobic process that can also occur in the water column; 3) Denitrification: the reduction of nitrate to N_2 gas, this is often fueled by nitrification; 4) anammox: the anaerobic oxidation of ammonium by nitrate; 5) Dissimilatory Nitrate Reduction to Ammonium or DNRA: this is an anaerobic process that keeps nitrogen in the system making it available for other biological uses, most importantly by phytoplankton. Figure courtesy of R. W. Fulweiler.

In contrast, N fixation converts N_2 gas into a biologically useable form of N. N fixation in both the water column and sediments has traditionally been considered to have a minor role in the ocean N cycle (Codispoti 2007; Galloway et al. 2004; Howarth et al. 1988a). However, several lines of evidence indicate the importance of N fixation in a number of marine systems. In the open ocean, recent work has shown that nitrogen fixing organisms are more abundant and diverse in the water column than previously thought, and may thus provide a significant source of N (Davis and McGillicuddy 2006; Zehr et al. 2001). In shallow coastal systems, it has been shown that sediment N fixation is an important process with rates equal to or greater than observed denitrification rates (Fulweiler et al. 2007; Gardner et al., 2006; McCarthy et al., 2008). It has yet to be established whether or not N fixation is a significant process in shelf sediments.

Of course there are many other important sediment N cycling pathways. Two other biologically mediated N cycling processes have recently been shown to be important in marine sediments. First, in addition to the classic or canonical denitrification ($NO_3^- \rightarrow N_2$ gas) discussed above, a newly discovered process, anammox, also removes N as N_2. Anammox is the anaerobic oxidation of ammonium by autotrophic bacteria. It appears to be a significant source of N removal in marine systems accounting for almost 70% of N loss in continental shelf sites (Thamdrup and Dalsgaard 2002) and up to 50% of N loss in the global ocean (Dalsgaard et al. 2005). Second, Dissimilatory Nitrate Reduction to Ammonium (NH_4^+) or DNRA is an anaerobic process that, unlike denitrification and anammox, retains N within the system and thus could potentially increase primary productivity (Gardner et al., 2006).

How these processes interact to determine the fate of N in marine sediments and ultimately, the global ocean N budget, is crucial for understanding of marine biogeochemical cycles (Gruber and Galloway, 2008). While some estimates have suggested that the oceanic fixed N budget is balanced, they are plagued with gross uncertainties (Gruber, 2004). More recent estimates indicate that the ocean N budget is unbalanced with a substantial N deficit, although these budgets also contain considerable uncertainty (Brandes and Devol, 2007; Codispoti et al., 2001; Deutsch et al., 2007).

Finally, in coastal areas, sediment organic matter decomposition and the associated nutrient regeneration can influence water column oxygen conditions, nutrient concentrations, and rates of primary production (Zeitschel, 1980; Nixon and Pilson, 1983; Nowicki and Nixon, 1985; Giblin et al., 1997). For a variety of systems, sediment nutrient release supplies a substantial fraction of the total demand for nutrients by phytoplankton (e.g., Potomac River Estuary, Callender and Hammond, 1982; North Carolina estuaries, Fisher et al., 1982; Baltic Sea, Koop et al., 1990; Chesapeake Bay, Cowan and Boynton, 1996; Patos Lagoon (Brazil), Niencheski and Jahnke, 2002). In turn, water column primary production deposited to the benthos or filtered from the water is also an important food source for sediment fauna and can have direct control on species abundance and distribution (Kemp and Boynton, 1981; Oviatt, 1994; Moodley et al., 2005). Such strong benthic-pelagic coupling is an important characteristic of shallow marine systems. Evaluating how benthic-pelagic coupling varies in the dynamic MAB shelf/slope environment will require a targeted process studies to supplement the core infrastructure of the Pioneer Array.

Continental Shelf Carbon Cycling

Because the oceans contain greater than 50 times more CO_2 than the atmosphere, even small perturbations in the ocean carbon cycle can result in substantial changes in the atmospheric concentration of CO_2. While continental margin systems are known to be very productive regions supporting a variety of marine ecosystems, the role of these systems in the global carbon budget has been a long-standing question.

Recent compilations of observational estimates document that variability in coastal air-sea CO_2 fluxes is large, and suggest that mid- and high-latitude systems generally act as sinks of atmospheric CO_2, whereas subtropical and tropical regions generally act as sources (Cai, et al., 2006, 2011; Borges et al., 2005). However these studies also acknowledge significant uncertainties in the estimates, arising from the difficulty in extrapolating data collected on individual cruises conducted with limited spatial and temporal coverage to fluxes representative of an entire continental shelf. In this regard, coupled biogeochemical-physical modeling frameworks provide an approach to quantify carbon and nutrient fluxes in continental margins. These models integrate theoretical knowledge and laboratory measurements and complement field-based approaches (reviewed in Moisan, 2010). Representation of the biogeochemical processes ranges from relatively simple nutrient-phytoplankton-zooplankton aggregate formulations (e.g., Powell et al, 2006) to multifunctional group representations of the marine ecosystem (Fennel et al., 2006; Lehmann et al., 2009).

Hofmann et al. (2011) provided an extensive review on the current state of carbon-cycling modeling in the context of a model developed for the northeastern North American (NENA) shelf region. The NENA model includes a high-resolution circulation model and a detailed biogeochemical model for coastal carbon and nutrient cycling. This coupled modeling system has been used to investigate the role of sediment denitrification as a nutrient sink (Fennel et al., 2006), the controls on air-sea carbon fluxes on the NENA continental shelf (Fennel et al., 2008), the cross-shelf export of particulate organic carbon (Fennel and Wilkin, 2009), and the role of dissolved organic matter dynamics in coastal ocean biogeochemical cycling (Druon et al., 2010). These studies show that modeling shelf carbon cycles require improved understanding of many process that control the flow of organic and inorganic carbon in and out of the shelf system, including exchanges with open-ocean, land, air, and sediment. Moreover, the key to model refinement is the ability to determine the rates and processes that have the largest impact on the relevant carbon pools and flows.

Improving coupled biogeochemical-physical models therefore requires evaluation of inputs of sediments, nutrients, fresh water, carbon from land, elemental fluxes between the sediments and the water column, air-sea fluxes of gases and nutrients, primary production, respiration, and cross-shelf exchange. Taking air-sea flux exchange, CO2 crosses the air-sea interface mainly by diffusion, which is controlled by the air-sea gradient in gas partial pressure *p*CO2, the gas solubility, and near-surface turbulence (Sarmiento and Gruber, 2006). The levels of pCO_2 in the surface mixed layer of the ocean is governed by the concentration of DIC and alkalinity, which are themselves influenced by riverine input, circulation, calcification associated with photosynthesis, and respiration.

In short, the strong linkages between and among these key processes that control organic and inorganic carbon cycles in the coastal ocean underscore the importance of making more in-situ observations of these processes, so that they can be correctly represented in models. The Pioneer Array will provide unprecedented opportunities to achieve this goal.

Phytoplankton Production, Distribution and Assemblages

As indicated by the preceding discussion, a range of physical processes (including shifts in the cross-shelf position of the front, variability of frontal structure, seasonal patterns of stratification and vertical mixing across the front, and regional event-scale forcing) will impact nutrient fluxes and material transport in the Pioneer Array domain, and thus the productivity, distribution and composition of phytoplankton assemblages. Synoptic observations suggest that there is enhancement of phytoplankton biomass within the shelfbreak front (Marra et al., 1990). Analysis of ocean color signals in the Middle Atlantic Bight also indicate enhanced levels of surface chlorophyll at the shelfbreak front during the late spring (Ryan et al., 1999; Ryan et al., 2000). Among the broad science questions relating to the phytoplankton community in the MAB shelfbreak region are:

- What controls phytoplankton production and biomass across the outer shelf, shelfbreak and upper slope (e.g., nutrient supply, light, grazing, advective processes)?
- How do these physical, chemical and biological factors determine horizontal and vertical distributions and composition of phytoplankton assemblages?
- How do various controlling factors and the composition of phytoplankton assemblages/biodiversity vary over event, seasonal, and inter-annual time scales?

The core observations from the Pioneer Array moorings and mobile vehicles will include vertically resolved time-series measurements of bulk bio-optical properties (including chlorophyll fluorescence, backscatter, and PAR). In combination with measurements of physical variables and nutrients provided by moorings and mobile systems, such information will allow assessment of phytoplankton responses to variability in nutrient fluxes, mixing/stratification, and other physically driven processes across a range of time and space scales. However, to address many aspects of the above questions, additional process studies will be required to estimate key rates, define distributions, composition and variability of phytoplankton assemblages and characterize grazer communities.

An example of a temporally focused investigation that could complement the Pioneer Array observations is the recent study of Hales et al. (2010). This study also highlights unresolved questions regarding physical processes in the front region that may influence biological productivity, and points to the value of information on spatial and temporal patterns of phytoplankton community composition beyond what will be obtained with the core Pioneer Array instrumentation. Based on high-resolution, towed vehicle surveys across the MAB shelfbreak front in summer (vertically stratified conditions), Hales et al. (2010) demonstrated strong cross-front differences in vertical nutrient fluxes referenced to light, nutrient and density fields. Seaward of the front, the base of the euphotic zone and the base of the pycnocline were at comparable depths and turbulent mixing, vertical nutrient gradients and upward nutrient fluxes into the euphotic zone were low. Shoreward of the front, the base of the euphotic zone extended below the pycnocline into a zone of stronger turbulent mixing, vertical nutrient fluxes were much greater, and fluxes were enhanced by biological uptake in the lower euphotic zone (which sharpened vertical nutrient gradients). The physical mechanisms responsible for the patterns observed shoreward of the front were not clear from the available data or prior modeling studies (one possibility being secondary circulation in the front). In addition, how the cross-front pattern evolves seasonally could not be resolved from this short-term, intensive study. Hales et al. (2010) also concluded that nutrient flux ratios and bio-optical properties indicated differences in phytoplankton community structure across the front and vertically in the stratified water column, but lacked the direct evidence to assess this or potential grazing impacts on the phytoplankton biomass and community structure.

As indicated by the example study of Hales et al. (2010), additional focused process studies could significantly enhance the scientific impact of the core observations obtained by the Pioneer Array. Such augmentation of the network will also be critical for implementing and validating next-generation coupled physical/biological/biogeochemical models for this region. Characterization of phytoplankton assemblages at least to the level of functional groups defined by size and forms will be quite valuable for model development, along with information on bulk composition (e.g., chlorophyll:organic carbon; silicate and calcite content) and key physiological parameters (e.g., photosynthesis-irradiances responses, nutrient uptake kinetics, temperature-dependence of growth and respiration, etc.). Along with providing a time-series context of core observations, a key role for the near real-time data obtained by the Pioneer Array observatory may be to guide targeted sampling of specific features across the front region, and thus optimizing resources and effort for additional process studies.

Controls on the Distribution and Abundance of Organisms at higher Trophic Levels

While the primary emphasis when designing the Pioneer Array was the link between cross-shelf exchange processes, nutrient transport, and primary productivity, the observatory will also offer a range of opportunities for basic research relating to organisms at higher trophic levels. Important issues include: habitat definition and spatial distribution relative to the shelfbreak front; biodiversity in the shelfbreak front and adjacent shelf and slope water masses; inter-annual variability of distribution and abundance of marine organisms and its relation to physical forcing and nutrient availability; and marine conservation issues.

The abundance, community structure and diversity of mesozooplankton and micronekton in the Gulf of Maine and Georges Bank, are significantly affected by along- and cross-slope advection of mesozooplankton and micronekton populations in slope waters (Miller, et al., 1998; MERCINA, 2004; Ji et al., 2008; Pershing et al., 2010). Links between climate-related signals and the distribution of zooplankton over the continental slope have also been documented for this region. The abundance of arctic cold-water zooplankton species has been increasing on New England and Scotian Shelf while warm-water species have been decreasing, and concurrent with an increase in phytoplankton concentrations small zooplankton abundance has been increasing (Head et al., 1999; Head and Pepin, 2007 and 2010; Head and Sameoto, 2007). Temporal shifts in abundance the copepod, *Calanus finmarchicus* are well correlated with continental slope temperatures as well as the North Atlantic Oscillation index from roughly three years prior (Pershing et al. 2001). *C. finmarchicus* was a target species for examining climate change impacts in the Northwest Atlantic GLOBEC program, and there is an extensive literature on the temporal and spatial variability of *C. finmarchicus* and other zooplankton over Georges Bank and in the central Gulf of Maine that provides a solid foundation for future studies of zooplankton in the Pioneer Array region.

Among macrozooplankton, euphausiids are a key component in the Northwest Atlantic ecosystems (Parsons and Lalli, 1988; Cochrane et al., 1994, 2000), and include important predators on *C. finmarchicus* (Lewis and Sameoto, 1988a, b, c, 1989; Sameoto and Herman, 1990). Micronekton (e.g., mesopelagic fishes, shrimp and squid) consume mesozooplankton and euphausiids and are themselves prey for higher trophic level predators (Corten, 2001; Fock et al. 2004; Sutton et al., 2008). Dense aggregations of mesopelagic fishes have been found along shelf slopes and into basin areas of the Northwest Atlantic (Sameoto et al., 2002; Gartner et al., 2008). A number of euphausiids and mesopelagic fishes vertically migrate from depths more than 100 and 400 m, respectively, to the surface at night to feed. These animals can also migrate horizontally between shelf and slope regions, and thus can influence carbon export and storage in deep waters (Longhurst and Harrison, 1989) as well as impact food web structure and ecosystem dynamics in the shelf/slope region.

The MAB shelfbreak region is an important area for commercial fishing, and there are numerous species within the region that have been extensively studied by fisheries scientists. Along with fish, other commercially important species present at the shelfbreak at various times of the year include the American lobster and the northern short-finned squid. Shelf/slope exchange dynamics and the features they affect, such as the cold pool position, are reflected in spatio-temporal distributions of numerous other species (Hoff and Ibara, 1977; Steves et al., 2000). The juxtaposition of warm water of subtropical origin (beneficial to metabolism) with cooler, productive shelf water, creates an edge effect that concentrates large species such as swordfish, tunas, and sharks (Podesta et al., 1993; Lutcavage et al., 2000; Campana and Joyce, 2004). Physical processes also strongly affect larval transport and population connectivity, particularly for coastal and estuarine-dependent species. Mortality of coastal and oceanic fishes is extremely high during the first days to months of life, typically well upwards of 90% (Sissenwine, 1984; Houde 1998a), and changes in mortality as small as 1-2% can half or double survivorship. Transport of pelagic fish larvae to highly favorable nursery habitat or alternatively to unfavorable pelagic habitat can thus play a dominant role in determining the impacts of predation, starvation, and suitable temperature on stock recruitment (Houde, 1989b, Hare and Cowen, 1991; Hare and Cowen, 1993), with impacts on adult biomass measured in millions of tons and persisting over several years. Such a scenario was observed for the valuable haddock fishery off New England when an episode of unusual westward transport off Georges Bank in 1987, reinforced by unusually low volume of salinity intrusion shoreward across the shelfbreak front, caused retention and enhanced survival on the MAB shelf. These conditions resulted in a record for year-class recruitment (Pollacheck et al. 1999).

For many species in the MAB, the shelfbreak presents a barrier between offshore larval supply (as determined by adult distribution and migration to the south and north) and estuarine and nearshore recruitment habitat. For example, bluefish and some other species have a complicated migratory pattern that involves transport by the Gulf Stream, potentially onshore transport to the shelfbreak via warm-core rings, and then onshore transport across the entire shelf to estuaries (Hare et al. 2002). Migration onto the shelf is restricted by the shelfbreak front, and accumulated larvae move quickly across the shelf to recruit in pulses during periods favorable to cross-front transport (Hare and Cowen; 1996). Fish larvae are far from being conservative tracers and much is yet to be explored regarding the selective permeability of fronts at critical life history stages and how larval behavior, such as vertical migration or position maintenance in the water column, interacts with physical transport mechanisms (Boehlert and Mundy, 1988; Govoni and Pietrafesa, 1994; Grothues and Cowen, 1999; Hare et al., 1999, Grothues et al., 2002).

By providing capabilities to resolve meso- and submeso-scale physical and biogeochemical processes, and cover the temporal scales from events, to seasonal and inter-annual variability, the Pioneer Array will provide a novel context for studies of zooplankton, ichthyoplankton and nekton. The ability to observe episodic but potentially highly influential transport events could be of particular importance in assessing the relationship between physical processes, larval transport and recruitment to adult populations. Targeted observational studies of the front which include drifters or isopycnal floats would also help evaluate Lagrangian properties of cross-shelf exchange processes and address questions relating to larval transport. By combining shipboard surveys using traditional sampling gear with newer acoustic and optical sensors, spatial and temporal distributions of mesozooplankton, micronekton and adult fish may be resolved on scales comparable to those observed for physical properties by the Pioneer Array, and provide the basis for a new level of understanding of physical-biological coupling in the shelfbreak region.

The shelfbreak also constitutes key habitat for numerous species of seabirds, sea turtles and marine mammals. Many of these animals preferentially or exclusively occupy the shelfbreak and slope for much of the year. Over the past several decades, species from six families of Cetacea have been sighted in the Pioneer Array area, ranging from large baleen whales to small porpoises (Read et al., 2011). The shelfbreak provides important habitat for several species including sperm and pilot whales, Risso's dolphins, and the cryptic beaked whales (Best et al. in revision; Kenney and Winn, 1986). The shelfbreak is also a migratory corridor for North Atlantic right whales between their summer feeding grounds in the Gulf of Maine and winter calving grounds off Georgia and northeast Florida (Firestone et al., 2008).

Marine mammals aggregate along frontal systems and bathymetric gradients at a variety of spatial scales (Davis et al., 1998; Cañadas et al., 2002), but little is known about the relative ecological importance of these two habitat features, especially in areas where they co-occur (Selzer and Payne, 1988; Baumgartner, 1997; Davis et al., 1998; Davis et al., 2002). Fronts are believed to aggregate prey items at various spatial and temporal scales (Olson and Backus, 1985; Olson, 2001). However, uncertainty exists over the extent to which variation in the strength and location of oceanographic fronts influences the distribution of top predators. The Pioneer Array offers the opportunity to detect and quantify the distribution, seasonality, and biodiversity of marine mammals in relation to a well-resolved shelfbreak environment. Placing observers on process cruises and performing focused tagging and tracking efforts for marine mammals could provide new insight into their habitat selection and behavior. With resolution of multi-scale oceanographic, nutrient, and phytoplankton fields, the Pioneer Array also presents a unique opportunity for biologists to study many aspects of marine mammal ecology in a more holistic ecosystem context.

Extreme Events: Storms and Air-Sea Interactions
While substantial progress has been made in the past decade in making direct measurements of air-sea momentum, mass and buoyancy fluxes, these measurements were mostly made in an environment with wind speeds less than 20 m/s (Edson et al., 2007). The lack of direct surface layer measurements results in little information on air-sea exchange in severe storms, representing a real impediment to forecasting storm tracks and intensity. The Pioneer Array will provide long-term, continuous, direct measurements of momentum, heat, and mass fluxes in a region located along a frequent track for storms. These observations can greatly increase our understanding of storms, their role in air-sea exchange, and their impact on the physics, chemistry, and biology of the oceans.

Numerous studies have also demonstrated the necessity of considering coupling of atmosphere-ocean-waves in order to realistically represent the Marine Atmosphere Boundary Layer (MABL) dynamics. Several major processes that warrant more study include the following:

- As air is blown across the coastal ocean, air-sea temperature and humidity differences are generated. This leads to changes in near-surface stability and surface stress as well as latent and sensible heat fluxes (Sweet et al., 1981; Hayes et al., 1989). Changes in the near-surface stability will modify the well-known neutral logarithmic wind profiles within the MABL, such that the vertical gradients of wind velocity, air potential temperature and humidity are increased in stable condition or decreased in unstable conditions (e.g., Liu et al., 1979; Stull, 1988).
- As air temperature and moisture start to respond to the air-sea flux exchange, the atmospheric pressure also changes (Lindzen and Nigam, 1987), leading to a spatial pressure gradient

which can drive secondary wind circulation (Wai and Stage, 1989).

- The ocean surface currents can impact the relative motion of air, acting to change the surface stress, thus affecting the atmosphere as well as feeding back onto the ocean via surface wind forcing and Ekman pumping (Cornillon and Park, 2001).
- Large ocean waves affect momentum, heat and moisture flux exchange, and can influence cyclone genesis by providing a source of low-level positive vorticity (Doyle and Warner, 1990; Holt and Raman, 1992).

Low-level jets (LLJs) can form within a few hundred meters of the ocean surface. LLJs are the strongest either when the background wind flow is along the ocean temperature front, so that changes in air temperature across the SST front enhance the jet via thermal wind, or when warm air is advected over a cold surface (Wayland and Raman, 1989).

All above-mentioned processes occur frequently in the Middle Atlantic Bight. Combining in-situ observations from the Pioneer Array with coupled air-sea-waves modeling experiments will significantly advance the understanding of heat, moisture, and momentum exchanges in the coastal ocean.

The science questions that can be addressed by the Pioneer Array are not limited to the broad themes discussed above. Both individual scientists as well as large groups with inter-disciplinary interests will have opportunities to add sensors, mobile assets, moorings, or satellite products via the core program proposal process at NSF. Similarly, regional modeling efforts are likely to include data from the Pioneer Array for assimilation among other contributions. In addition to the proposed science dealing directly with use of the Pioneer Array, links to other science programs will extend insights from the Pioneer Array science to larger spatial and temporal contexts (see Section VIII).

V. Pioneer Array Design

The basic design of the Pioneer Array has been described in the Final Network Design. We briefly describe the major components of the array and then report the issues and recommendations from the discussions at the workshop. The basic goal of the discussions was to identify minor changes to the design that would enable better capabilities to answer questions from the science themes listed above. In Section VI, a number of potential enhancements to further address the major science themes are summarized.

The Pioneer Array consists of three separate elements: a mooring array which spans the outer shelf and upper slope; a group of gliders; and a pair of AUVs which will transfer data and re-charge batteries between missions at two docking stations located at the most onshore and most offshore of the moorings. The Pioneer moored array will include vertical profilers with multiple sensors with multi-function bottom nodes as well as surface buoys with telemetry and power generation on some moorings. A plan view of the array in the configuration recommended by the workshop consensus appears in Figure 5.

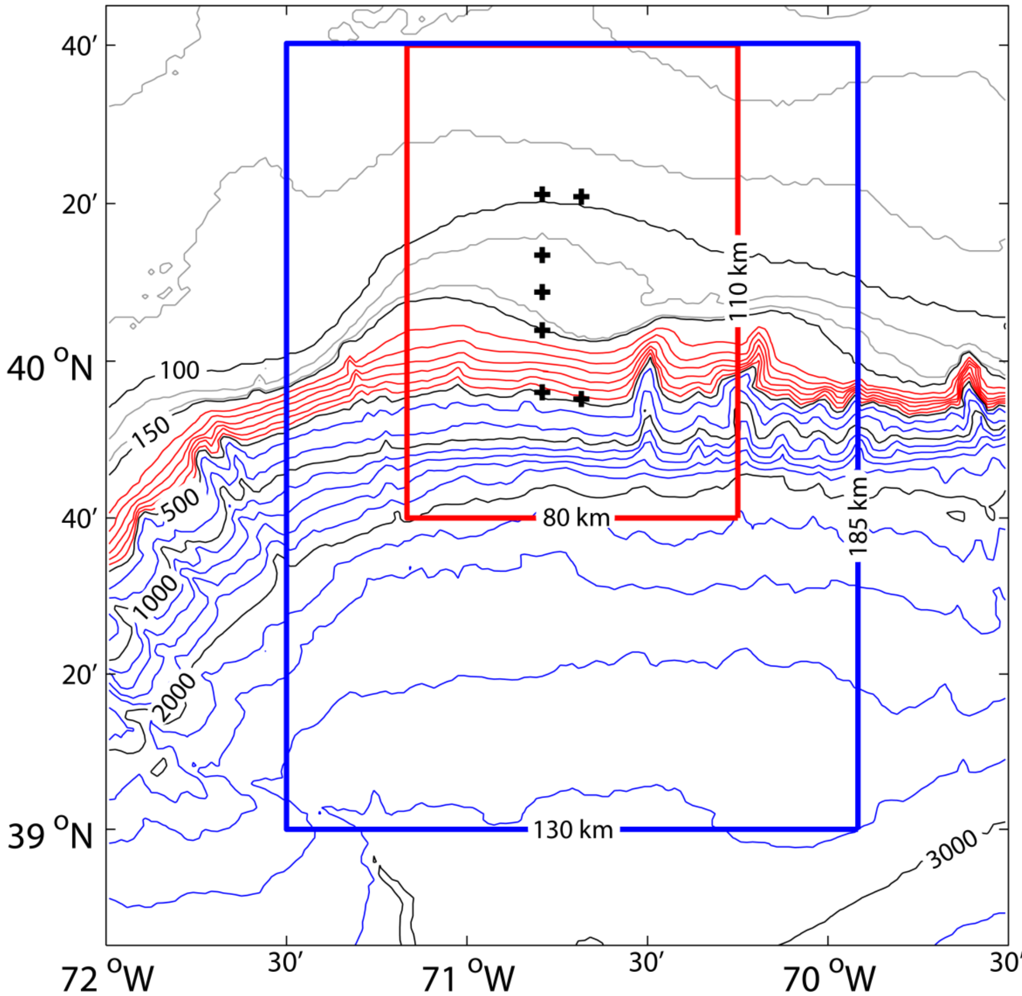

Figure 5- Recommended configuration of the Pioneer Array based on workshop discussions, engineering considerations, and public input. The red rectangle denotes the operational area for AUVs and the blue box indicates the operational area for gliders. Figure courtesy of A. Plueddemann. Refer to Figure 1 for the array location in the regional setting.

Moorings

The basic configuration of the mooring array consists of 7 primary sites (which may have two moorings at a site) with five moorings in a cross-shelf line oriented north to south and two flanking moorings upstream of the most onshore and most offshore moorings. The moorings will have vertical profilers providing four profiles of vertical structure per day at the continental shelf sites and two profiles per day at the two continental slope moorings.

The preliminary design presented at the workshop positioned the moored array between the 130 m and 500 m isobaths. Concerns were raised at the workshop that the mean position of the foot of the front was located shoreward of the most onshore mooring in this configuration, and that near-bottom intrusions penetrated much further onshore. Examples of cross-shelf sections from recent cruises in this area indicated that the 130 m isobath was more commonly near the center of the front and in extreme cases the entire front was located shoreward of the 130 m isobath. In the two weeks following the workshop, Project Scientist Al Plueddemann, in consultation with the co-organizers of this workshop, recommended shifting the shallowest mooring further inshore to the ~ 90 m isobath. A cross-section of the modified design appears in Figure 6. In this configuration, the mean position of the foot of the shelfbreak front is just seaward of the most onshore mooring. The three middle moorings, which includes the central mooring with extensive meteorological instruments on the surface buoy, is located near the expected mean position of the shelfbreak frontal jet. Existing climatologies and numerical model fields were examined as input into the final choices. Other factors were considered in the workshop recommendations including operational and logistical concerns.

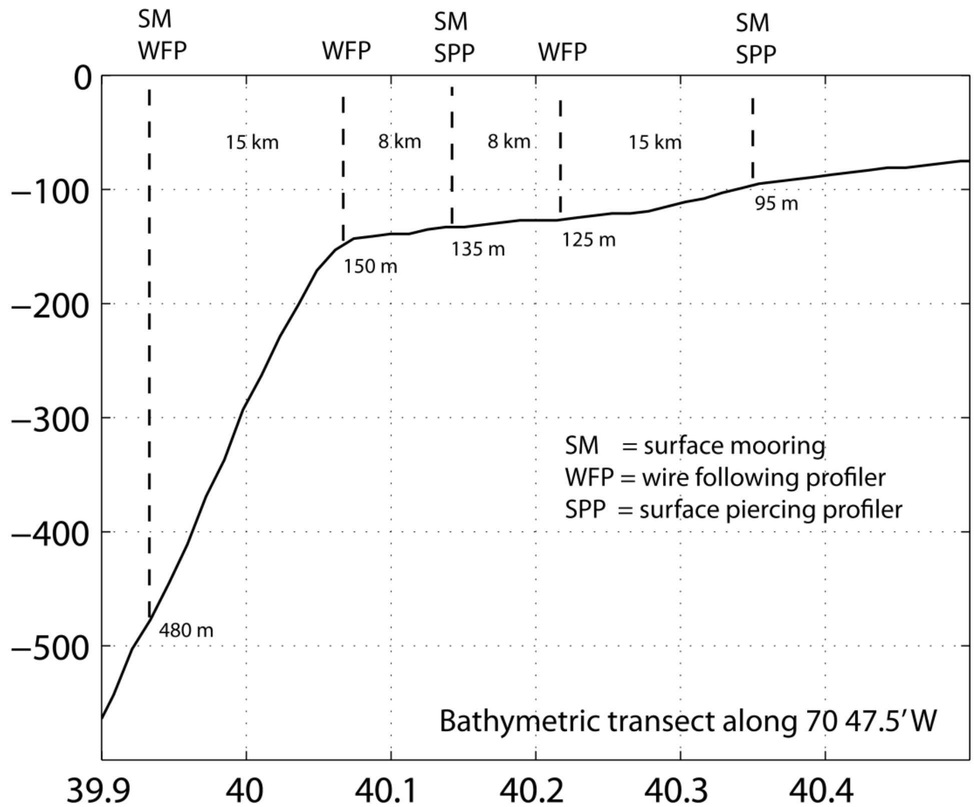

Figure 6: A schematic of the primary mooring line indicating the relative position of the moorings for the recommended configuration based on workshop discussions. The mooring capabilities are labeled. Figure courtesy of A. Plueddemann.

A second important line of discussion involved the nature of the nutrient sensors on the moorings. In the initial design, the nutrient sensors on the moorings would all be on vertical profilers and would be the optically based nitrate sensor in order to obtain continuous measurements in the vertical. However, workshop participants suggested that deployment of reagent-based in situ nutrient analyzers may also be desirable at the attachment points located five meters below the surface buoys for the onshore and offshore moorings. While sampling with the reagent-based analyzers would be more limited temporally, time series measurements for multiple nutrients could be obtained at a few locations. These systems could also provide a cross-check for the optically based nitrate measurements. Having measurements with a larger suite of nutrients would track shifting ratios between nutrients and temporal shifts in shelf and slope water nutrient end members, an important aspect of cross-shelf nutrient fluxes.

The initial design included near-surface measurements of pCO_2 at several locations. The in-water pCO_2, along with wind speed and temperature, is critical for estimating the air-sea flux of CO_2. The initial design also has pH sensors at 5 m depth at the onshore, central, and offshore moorings. The pH measurements will serve several purposes. First this supplies a second carbonate parameter (along with *p*CO2) that allows solution of the system of carbonate equations, and thus estimates of total alkalinity (TA) and dissolved inorganic carbon (DIC). The addition of pH sensors will also provide valuable time-series information relevant to assessing ocean acidification (as is TA). Further, since variability of the carbonate system can be caused by both biological and thermodynamic perturbations, and the thermodynamic component can be readily characterized using the temperature and salinity data provided by the array, the residual component will provide valuable information on the net biological processes. We recommend that, if possible, pH sensors be added to the multi-function nodes at the bottom for the central and offshore moorings. The offshore mooring is particularly important for near-bottom pH measurements as it would characterize the offshore nutrient pool, which is poorly known at the present time.

In terms of the existing network design, it was pointed out during the workshop that the various illustrations of the Pioneer Array included in the OOI documents do not include specific information on the sensor configurations for different moorings within the array. Figure 7 shows a list of sensors appearing at the different moorings on the primary cross-shelf line based on the Final Network Design. Suggested modifications of sensor configurations made at the workshop had not yet been reviewed by OOI engineers, so those suggested modifications are not included in this figure.

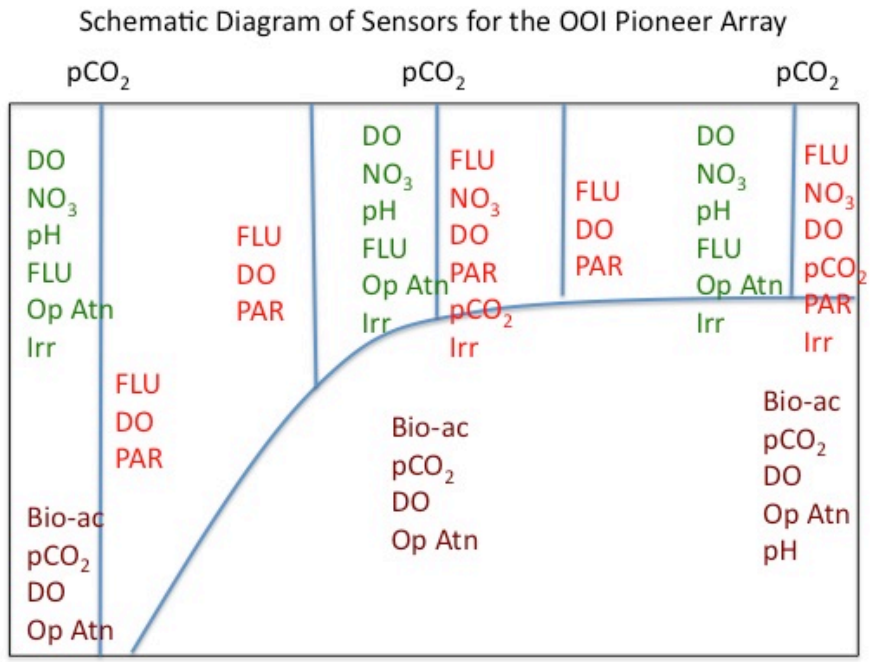

Figure 7**:** A sub-set of sensors on the moorings located on the primary cross-shelf mooring line from the Final Network Design. The sensors marked in green are fixed near the surface (nominally 5 m depth), the sensors in red are on the profilers, and the sensors in brown are ~ 2 m above the seabed. While many of the sensor symbols are self-evident, "Bio-ac" refers to acoustic backscatter measurements to estimate biomass of fish and zooplankton, "Op Atn" refers to optical absorption/attenuation, "Irr" refers to spectral irradiance, and "PAR" refers to photosynthetically active radiation. There are additional meteorological sensors on the surface as well as velocity measurements and temperature/conductivity sensors that are not listed as this figure emphasizes bio-geochemical sensors. "FLU" designates a three-channel optical instrument (measuring chlorophyll *a* fluorescense, CDOM fluorescence, and optical backscatter) and "DO" denotes dissolved oxygen.

Gliders

A core component of the Pioneer Array will be deployment of mobile assets to sample the shelfbreak environment over an extended period of time. Gliders are an important element because of their long duration, ability to reach significant depths (1000 m), and simultaneous use of multiple units (up to six in the present plan). These mobile assets can provide both regularly structured sampling (repeat lines or patterns) as well as adaptive sampling necessary to resolve transient features, for example, the periphery of a warm core ring.

Discussions during the workshop focused on the most important scientific goals for the fleet of gliders. The need for guiding principles for use of the gliders was articulated by Dr. Bill Bergen, an engineer representing the OOI program. The guiding principles essentially define objectives for either individual or groups of gliders, and assist in the prioritization of glider efforts within the fleet. After extensive discussions during the workshop, three separate goals were considered important for the gliders:

1. establishing upstream conditions over the outer shelf and upper slope necessary for numerical models;

2. providing alongshelf coverage down the expected mean axis of the shelfbreak jet and adjacent slope waters to identify fluxes between the shelfbreak front and the slope waters offshore; and

3. resolution of important slope features such as slope eddies (including warm core rings) and shelf streamers.

The first goal, resolving the water mass and velocity structure upstream of the study area is extremely important for proper performance in regional numerical models of the continental shelf and slope. Since the mean flow is to the west over both the shelf and slope, establishing a regular cross-shelf line at the eastern boundary of the glider domain in Figure 5 would be essential to understand the variability of water mass structure and the frontal jet advecting into the mooring array. Either linear offshore transects or triangles which optimize the maximum coverage in the presence of the mean flow would serve this goal.

The second goal serves a dual purpose. Frontal meanders are an important source of variability within the front and propagate from east to west with a phase velocity of 10-20 cm/s. Properly resolving the structure of frontal meanders is important to quantifying cross-shelf exchange as well as reducing uncertainty in numerical models. Glider tracks running roughly east-west down the center of the mean position of the jet, in combination with parallel sections immediately offshore, could provide estimates of eddy fluxes of heat and salt between the frontal region and the slope waters further south. This could be resolved with a rectangular pattern although triangles may offer some benefits as well.

The third goal is to resolve slope features that are important for assessing cross-shelf exchange. With the original plan for 6 gliders, up to 4 gliders could be directed towards the edges of warm core rings, across southward flowing streamers of shelf water moving towards the Gulf Stream, or other types of features such as pigment maxima from ocean color images or local maxima in ecosystem models. There are presently a number of adaptive sampling algorithms being developed and applied to modeled ocean fields (e,g., Lermusiaux, 2007; Chao et al., 2008), and the recent Cyberinfrastructure exercise in November, 2009 off New Jersey is an example of how models may be used to plan glider missions interactively.

There was also interest expressed at the workshop in having gliders make turbulence and mixing measurements. However, it was noted that suitably equipped gliders will not be part of the core instrumentation planned for the Pioneer Array, but might be provided through complementary projects.

Of necessity, there will be some level of overlap between normal operations of the glider fleet and Principal Investigator funded research which might have specific requirements for the duration of process experiments. Further discussion of some of these issues is summarized in Section VII (Science-Operational Interface).

Autonomous Underwater Vehicles

AUVs will play an important role in the Pioneer Array. These powered vehicles will be fast enough to follow mission tracks through strong currents and also have more power and space than gliders to carry sensors. The current design will employ two AUVs operating from docking stations, with a third available for additional process studies as well as outreach activities. The AUVs are anticipated to do missions roughly once a week with endurance of roughly 200 km in terms of track length.

The recommendation at the workshop was for the offshore AUV to conduct prescribed missions oriented cross-shelf along the mooring line and extending further onshore than the most shoreward mooring. This would allow periodic transects of high-resolution structure of the nutrient (nitrate) field in the cross-shelf for comparison with the more spatially limited but temporally detailed nutrient data from the vertical profilers on the moorings. Extending further onshore of the most shoreward mooring would also better document shoreward excursions of the front. It was also recommended that the vehicle then move along-shelf a short distance (10-15 km; possibly orienting with the flanking moorings) and then transit offshore and then along-shelf back to the offshore docking station. The two separate cross-shelf transects would provide some information on alongshelf frontal variability and cross-shelf penetration of slope water. The cross-shelf orientation of the transects from this vehicle allows for calculation of alongshelf fluxes of heat, fresh water, and nutrients.

The onshore AUV will have an important role in measuring alongshelf variability. The prescribed along-shelf orientation for missions would target estimates of eddy fluxes of nutrients and fresh water between the continental shelf and the frontal region, one of the primary science goals of the Pioneer Array. It was recommended that the mission should consist of two parallel alongshelf transects, with one oriented with the most onshore mooring and the second 10-15 km further onshore. The latter section is important for establishing the onshore extent of near-bottom intrusions of slope water as well as resolving shoreward translations of the front. Because variability is expected to be extensive seasonally as well as inter-annually, having one set of spatially consistent flux measurements will be critical for evaluating cross-shelf fluxes in numerical models.

An important aspect of the AUV data suite is the choice of nutrient sensors. The original design envisaged the use of a multi-channel reagent-based in situ nutrient analyzer. However, because of the long deployments in the field through use of docking stations for repowering and data transfer (and thus limited opportunities to replenish reagents) and large vertical excursions of expected AUV missions (requiring a relatively high sampling frequency to adequately resolve vertical gradients), it was recommended that the nutrient sensor on the AUVs be switched to the optically based nitrate sensor. This would allow for high vertical and horizontal resolution necessary for establishing the relation between nitrate and onshore slope or offshore shelf water features. While there is a trade-off in the sense that the optically based sensor is limited to nitrate, the inclusion of multi-channel reagent-based nutrient sensors for lower frequency time-series measurements at the onshore and offshore moorings would help with assessing variability in nutrient concentrations and ratios. It was also suggested that the third AUV (to be operated from a ship during operations and maintenance cruises) could be equipped with a multi-reagent based nutrient sensor and provide high frequency, multiple-nutrient sampling over missions of ~1 week duration.

VI. Potential Enhancements

Expanding the Breadth of Pioneer Array Research

The components of the core infrastructure for the Pioneer Array are limited in terms of the sensor types, packages, and spatial coverage (number of moorings). For example, while the core instrumentation covers "bulk" bio-optical instrumentation, and some key chemical parameters such as oxygen, nitrate, pCO_2 and pH in addition to core physical oceanographic measurements, there is a need for further sensors for biological rate measurements as well as biogeochemical processes. Different moored profilers also have different sensor combinations, so that spatial resolution is not the same for all variables. This may necessitate additions to extend spatial and temporal coverage as well as to expand the types of sensors deployed in the array. For the core instrumentation, there are constraints on power, communications bandwidth, deployment and servicing requirements, and interfacing issues. Thus mechanisms to ensure effective use of the core Pioneer Array infrastructure as well as for adding enhancements must be addressed (see the following section on the science-operational interface). Over the planned deployment of the Pioneer Array, further progress in sensor capabilities for a range of variables, as well as new packaging options for extended sensor deployment, are to be expected. Thus capabilities for testing and integrating new systems must also be considered.

Examples of anticipated additions to the primary infrastructure of the Pioneer Array include:

- Add-on sensors to multi-function nodes near the bottom on three moorings.
- Additional stand alone moorings.
- Packages making measurements in the benthic boundary layer, at the sediment/water column interface, and in the sediments, both connected to the multi-function nodes and stand alone.
- Ship-based process cruises, including biological rate measurements as well as a range of other targeted measurements.
- Additional deployments of mobile assets or mobile assets with additional capabilities (such as turbulence and microstructure sensors).
- Inter-calibration or cross-comparison studies during periodic operations and maintenance cruises including additional nutrient measurements for determining ratios between various nutrients.
- Passive acoustics for characterizing marine mammal activity and migrations.

A substantial amount of discussion at the workshop related to resolving the boundary layer processes. Resolving the bottom boundary layer is important for nutrient and carbon cycling, cross-shelf transport of buoyancy, salt, and nutrients, frontal upwelling, and sediment transport. Enhancements to the core array infrastructure capable of measuring both the structure of the bottom boundary layer as well as biogeochemical processes at the water-sediment interface and in surface sediments were deemed a high priority. Similarly, stand-alone moorings may be necessary to characterize internal wave energy levels and high frequency contributions to vertical fluxes.

An important aspect of variability over the continental shelf is identification of signals propagating from upstream in the Gulf of Maine and Georges Bank. While the upstream glider line will be useful in this regard, it will not resolve all the signals from upstream. It will be useful to have either moorings or gliders located further upstream of the cross-shelf glider line that can differentiate between signals advecting from Nantucket Shoals and the Great South Channel versus those advecting from the south flank of Georges Bank. Further discussion of upstream influences and climate related signals appears in Section VIII.

Connections with other long-term coastal ocean and estuarine observing programs will also increase the utility of the Pioneer Array. For example, the University of Rhode Island has been studying Narragansett Bay over an extended period of time. Studies which enhance the understanding of exchange processes across the entire continental shelf would be extremely valuable. The Martha's Vineyard Coastal Observatory is another potential element in a more comprehensive cross-shelf system. High-frequency radar coverage by MARACOOS may be augmented by a bi-static system to significantly extend the offshore range of existing HF radar systems. The New England shelf would be an advantageous location for studies of bio-diversity across the entire shelf and Narragansett Bay. Similar bio-diversity corridors have been initiated over the Scotian shelf and in the Gulf of Maine.

Offshore, Line W has been occupied by moorings spanning the continental slope (Figure 1). While this line is scheduled to be removed at the end of 2013, hopefully future efforts can add more moorings extending across the continental slope to the Gulf Stream. In addition to the moorings, satellite observations of sea surface temperature, sea surface height anomalies, scatterometer winds, and ocean color will also enable the Pioneer Array data to be placed in a larger regional context.

Optimal sampling of the Pioneer Array requires a priori estimates of the state of the ocean during the sampling interval. To carry out such observations adaptively requires flexible and efficient platforms well matched to phenomena in a dynamic shelfbreak ocean environment. In the context of the Pioneer Array, the system to be controlled is the set of gliders and AUVs. High-resolution model nowcast/forecast data and measurements at regular time intervals (glider GPS fixes, etc.) could be combined to update the mission plans for the mobile platforms. While the recommendation during the workshop that two AUVs follow prescribed cross-shelf and alongshelf oriented paths limits adaptive sampling, there is a third AUV which could be used during process cruises which will also be equipped with the capability of measuring multiple nutrients.

The basic objectives for adaptive sampling include: (1) to provide the best possible data to address scientific hypotheses; (2) to augment observations in regions of greatest model uncertainty and/or in sub-regions of most energetic dynamic activity, so that models can be optimally updated with new data; (3) to ensure effective coordination of the glider/AUV network. With feedback control, and coordinated multi-unit mission plans, key regions of interest may be better identified and the utility of sampling data improved (e.g., by collecting gradient information across shelfbreak fronts). Observational System Simulation Experiments (OSSEs) have been playing an essential role in quantitatively assessing adaptive sampling strategies (e.g., Robinson et al., 1998). Research in this area to support interdisciplinary oceanographic studies at the Pioneer Array site should be encouraged.

VII. The Science-Operational Interface

An effective interface between science users and OOI at several levels will be required to fully utilize the research potential of the Pioneer Array. Two mechanisms for broad engagement between the ocean science community and OOI have been established. The **Program Advisory Committee** (**PAC**) within COL was formed in 2008 to advise the OOI Program Office, the Project Director (Tim Cowles) and the Implementing Organizations during planning and construction phases (see: *http://www.oceanleadership.org/programs-and-partnerships/ocean-observing/ooi/ooi-program-management/advisory-committees/*). The PAC role includes guidance on strategic planning for science programs and representing community input on OOI implementation and management. Within NSF, the **Ocean Observatories Science Committee** (**OOSC**) was established in October, 2010 as one of the standing committees coordinated by the University National Oceanographic Laboratories System (UNOLS). Larry Atkinson (Old Dominion University), Committee Chair, participated in the Providence workshop and provided a short presentation on the OOSC. The primary charge of the OOSC is to provide science community perspective to the OOI project team, NSF and other agencies regarding ocean observing plans and priorities. The OOSC is also intended to provide technical advice, participate in performance reviews of OOI and help identify and disseminate best practices for ocean observatories (technical and managerial).

At the program level, there are ongoing developments within OOI, COL and NSF in several key areas regarding the science users of the system. This includes establishing guidelines for PIs interested in pursuing proposals that would utilize and/or augment the Pioneer Array capabilities. Such guidelines had not been formalized at the time of the Providence workshop. However, it is anticipated that proposals to add instrumentation to the array will first undergo review by OOI for basic engineering feasibility (e.g., assessment of power, communications, mechanical and servicing requirements) with responses to PIs specifying required modifications, etc. This review process will require establishing a schedule that provides timely feedback so that PIs can respond to the OOI engineering review prior to submission of science proposals to NSF OCE. It is anticipated that proposals would then go through the standard review process, followed by an integration step for incorporating funded instrumentation and new data streams into the OOI network.

For the purpose of this white paper, we focus on the science-operational interface at the level of researchers who are interested in using the information from the Pioneer Array observatory and/or conducting complementary research projects that leverage the core array observations that will be collected over its five-year deployment period. At the level of both science and logistics planning (prospective individual PIs and collaborative groups) and operations (funded projects), ongoing dialog between OOI Operations & Maintenance and science users will be required. Aspects of the science-operational interface were noted in the preceding section (e.g., contingency plans for glider operations). Here, potential issues that were identified during the

Providence workshop discussions are highlighted that may warrant further consideration by OOI and NSF, and input to the OOI PAC and UNOLS OOSC from the potential user community. The following is not intended to be an all-inclusive list. Part of the ongoing dialog required between OOI and the science user community will have to be directed toward refining and optimizing the Science-Operational interface for the Pioneer Array during the transition between construction and operations.

- Setting science priorities for additions to instruments to the Pioneer Array infrastructure. There will undoubtedly be trade-offs to consider in terms of engineering criteria (e.g., power, bandwidth, mechanical and servicing requirements) and the scientific justification for addition of various instruments or instrument packages to the core array infrastructure. For example, while final power budgets for various Pioneer Array platforms had not been determined at the time of the Providence workshop, having some level of surplus power available for additional instrumentation is targeted. It is clear, however, that there will be constraints on the power available. Similarly, while the communications systems will be robust compared to most autonomous buoy systems, additions to the core system will have to be accommodated within a limited surplus bandwidth. Servicing requirements for additional instruments/packages will also be a key consideration. Servicing of the array moorings is presently scheduled at 5 (7) month intervals in summer (winter). The turnaround cruises are currently scheduled for April and September.

- Making use of the Multi-Functional Nodes (MFN) on buoys and bottom pods. In the OOI documentation up to the time of the Providence workshop, the MFN component had been defined only in broad terms. There are a number of basic issues to be addressed concerning how these will be made accessible to science users, including the mechanical configurations, how additional instrument packages can be connected, power budgets, communications protocols, available bandwidth and how packages will be serviced. This is particularly critical for instrumentation for measurements in the benthic boundary layer, at the seafloor and in the sediments. It should be noted that no instrumentation below about 2 meters off the seafloor is included in the Pioneer Array systems described in the Final Network Design. Thus instrumentation at the benthic MFN nodes, along with additional stand-alone packages, will be required for any studies addressing benthic boundary layer, benthic-water column exchange and sediment processes.

- Contingency Plans. The OOI O&M personnel will need to have a definition of science priorities to formulate response options in the event of failure of various system components. Again, trade-offs will be inevitable and in many cases observations that are important to a given discipline or targeted investigation may be compromised until repairs can be completed. How science users will have input into contingency planning and into the decision process as system failure/responses occur will need to be addressed.

- Optimizing the science return from ship-based work during O&M cruises. There are clearly limits to the extent of science operations that can be accomplished during the cruises where the primary objective will be to recover/deploy moorings or other intensive servicing operations. However, from the discussion at the Providence workshop, it was clear that opportunities for ship-based sampling on a recurring basis would serve a number of science objectives and strongly complement the observations made with the core instrumentation on the array. Similarly, equipping the servicing vessels with capabilities for obtaining high-quality along-track measurements of a range of near-surface properties would complement the array data sets and provide useful initial/boundary condition information for models. A number of sensors/analysis systems should be considered that could provide measurements of comprehensive suite of physical, chemical, and bio-optical variables, along with information on phytoplankton and zooplankton community composition.

- Inter-calibration of sensors deployed on the array (mooring and mobile systems), ship systems and independent user-deployed packages. Participants at the workshop stressed the importance of supplementing the baseline OOI sensor calibrations with additional measurements by the science community. The turnaround cruises offer one possibility for science community involvement in inter-calibration. The importance of inter-calibration at regular intervals was identified as a priority issue and warrants further discussion by oversight committees in the future regarding the most effective avenues to ensure that this is part of the routine maintenance plan.

VIII. The Broader Setting- Regional Context and Related Programs

The oceanographic setting for the Pioneer Array is subject to a number of important climate related signals. The continental shelf circulation is part of a large scale advective pathway from the Labrador Sea to Cape Hatteras (Chapman and Beardsley, 1989). The shelfbreak front and associated jet similarly extends from the Labrador Sea to Cape Hatteras (Fratantoni and Pickart, 2007). There is significant variability in the volume of shelf water in the Middle Atlantic Bight (Mountain, 2003) as well as long-term temperature trends due to the large scale advective signal (Shearman and Lentz, 2010). Recent studies (Greene et al., 2008; Greene and Pershing, 2007) have suggested that large scale advection of fresh water from the Arctic Ocean is likely to continue to result in the transport of low salinity anomalies equatorward in pulses with associated increases in stratification as well as shifts in the ranges of phytoplankton, zooplankton, and higher-trophic level organisms. While research continues on the nature of climate signals between the ocean and atmosphere in the north Atlantic Ocean including large scale wind stress anomalies and shifts in the meridional position of the Gulf Stream, the shelfbreak region has been particularly difficult to study because of the high degree of mesoscale and sub-mesoscale variability. Flagg et al. (2006) have shown the week to week variability of the velocity and temperature field across the shelf and slope off New Jersey as well as the inter-annual variability of the temperature across the continental shelf and slope. Rossby et al. (2005) have examined inter-annual variability of the Gulf Stream position and transports over an eleven year period and Schollaert et al. (2001) have studied the response of the pigment field over the slope sea in response to shifts in Gulf Stream position related to forcing from the North Atlantic Oscillation.

Future results from the Pioneer Array will need to be analyzed and interpreted in terms of the larger scale context including upstream variability within the Gulf of Maine and the Scotian shelf as well as larger scale variability of the atmospheric forcing. The contribution of nutrients from upstream sources (e.g. Townsend et al., 2010) will be important to consider in addition to the cross-shelf exchange processes which the Pioneer Array was designed to resolve. Due to the short time duration of the Pioneer Array (5 years), there is not the opportunity to explore multi-decadal signals. However, the intent is to identify some sub-sets of Pioneer Array assets that may be particularly critical for defining cross-shelf exchange of nutrients and ecosystem response so that some elements of the observatory may be incorporated into the regional component of the Integrated Oceanographic Observing System (IOOS).

Finally, the regional associations coordinating coastal ocean observing programs, NERACOOS and MARACOOS, offer important opportunities for joint investigations. NERACOOS may be running regional modeling systems that could assimilate include Pioneer Array data. MARACOOS also operates a MAB-wide High-Frequency radar network to map surface currents. As planning and construction moves forward, we anticipate that other federal agencies will become more interested in using Pioneer Array data and potentially conducting joint research such as inter-disciplinary process cruises.

IX. Summary

The Pioneer Array science workshop held in Providence RI on February 22-24, 2011 gathered 26 participants from 20 institutions along with representatives from OOI, NSF, and the Consortium for Ocean Leadership (COL). Workshop participants reviewed the broad science themes that have motivated the MAB Pioneer Array, the status of the OOI program, the basic array configuration (platforms and measurements), capabilities (mechanical, power, communications) and the OOI data management system. The workshop attendees also had extensive discussions to highlight opportunities where augmentation of the array or complementary process studies would expand the breadth of science themes capable of being addressed by the observatory.

The present white paper is intended to summarize meeting discussions, and inform potential science users of the capabilities of the present design of the MAB Pioneer Array for a wide range of research investigations focusing on MAB-specific topics. Important shelf-slope exchange processes are reviewed, followed by descriptions of four broad science themes that can be explored in the future using data from the Pioneer Array, including: nutrient and carbon cycling; phytoplankton production, distribution, and biodiversity/assemblages; extreme events, including storm response and air-sea interaction; and controls on distribution and abundance of zooplankton, fish, marine mammals, and other organisms from higher trophic levels. A summary of the present Pioneer Array Design as well as potential enhancements are also presented. It is our hope that the science community can use the information documented in this report to plan and carry out ground-breaking research projects that utilize and leverage the unprecedented observational capabilities and potential for modeling shelfbreak processes resolved by the Pioneer Array.

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Appendix A- Agenda for the Meeting

OOI Shelf/Slope Processes Workshop- Providence, RI, February 22-24, 2011

(***Numbered Sessions*** *indicate Plenary or Working Group discussion*)

****
Tuesday, February 22

0830 Breakfast and Registration

0930 Greeting & Logistics (Glen Gawarkiewicz, Ruoying He, Jim Nelson)

0945 NSF Perspective (Jean McGovern, Eric Itsweire)

1000 Science Background- Shelf Break Frontal and Exchange Processes- An Overview (Glen Gawarkiewicz)

1020 Biological/biogeochemical aspects of shelf break exchange processes and other potential areas for multi-disciplinary observational science (Jim Nelson)

1040 Modeling Shelf Break Processes- Physics and Ecosystem Dynamics (Ruoying He)

1100 Break

1120 Pioneer Array Configuration: Platforms and Measurements (Al Plueddemann)

1140 Pioneer Array Capabilities: Mechanical, Electrical, Power and Bandwidth (Sheri White)

1200 OOI Data Flow and Data Management Policy (Bill Bergen)

1220 Lunch

1315 Overview of Workshop Agenda and Working Group Assignments (Glen Gawarkiewicz)

1320 **Session I**. Pioneer Array Science – participants' areas of research interests.

Session Objective: Introduce participants' interests, ideas for science applications of the Pioneer Array, and general questions concerning the Design and Science Plan.
Format: Participants will provide a PowerPoint slide in advance of the workshop to be compiled by the organizers into a single file. In this session,
we will step through the slides and each participant will provide a brief summary of their research interests, ideas relating to updating the science plan for the Pioneer Area, and topics they feel should be considered regarding the Science Plan and the "science-operational interface". (Four minutes maximum per person.)

1500: Break

1530: **Session II**. Pioneer Array Science Themes.

Session Objective: Review Science Plan objectives in previous documents. Discuss most exciting inter-disciplinary science questions with respect to present design capabilities; priorities among design components needed to address the major science themes.
Format: Three Working Groups meeting concurrently

Working Group 1. Circulation, sediment transport/geology, acoustics
(Gawarkiewicz)

Working Group 2. Carbon/nutrient cycling and fluxes, bio-optics, ecosystem processes, living marine resources (fish, mammals) (Nelson)

Working Group 3. Atmospheric interactions, air-sea fluxes, modeling physical-biological interactions (He) [In workshop, this group was combined with Group 2]

1700: Brief Working Group Reports / Summary of Day's Discussion / Questions for follow-up discussion

1730 – 1930: Meeting room is available for follow-up discussions

No formal dinner planned.

****
Wednesday, February 23, 2011

0830: Breakfast

0900: **Session III**. The Science-Operational Interface (Part 1) – Moorings: Science, Siting, and Technology

Objective: Focused discussion on fixed-position observing assets, locations, package configurations and capabilities of present design; what are key operational considerations with respect to the science themes; what might be enhanced to better address the major science themes.

Format: Discussion in Working Groups

1030: Break
1100: **Session IV**. The Science-Operational Interface (Part 2) – Mobile Assets: Sampling, Sensors, Science objectives

Objective: Focused discussion on the mobile assets and their role in the Pioneer Array Science

Plan.

Format: Working Group discussions.

1230: Lunch

1330: **Session V**. Potential enhancements to the core Pioneer Array infrastructure.

Objective: Discussion of science applications of the observatory infrastructure beyond the "core" processes targeted in the Pioneer Array design. Examples of potential processes/research topics that can leverage the shelf/slope observatory. What might be effective strategies for expanding the scope of science applications of the Pioneer Array? Additional infrastructure requirements? How can the Pioneer Array contribute to further development & field testing of observational technologies and models?

Format: Working Group discussions

1500: Break

1530: **Session VI**. The Broader Context- Upstream Flows, Climate Signals, and the Regional Continuum

Objective: Discussion of how the Pioneer Array science can fit into a larger spatial/temporal context.

Format: A brief overview will be presented to set the context for discussion in plenary.

1700: Working Group Reports/Summary; topics/questions for follow-up discussion

1730 – 1930: Meeting room available for follow-up discussion

No formal dinner planned.

****
Thursday, February 24, 2011

0830: **Session VII.** Working Group Reports/Summary.

Objectives: Summarize the Working Group discussions regarding broad science questions; observatory issues and recommendations; the broader science context for the Pioneer Array.

Format: Plenary reports and follow-up discussion

1000: Break

1020: **Session VIII.** Broader Impacts and Connections to other programs and agencies

Objective: Discussion of interactions with other agencies & programs; future steps toward developing effective interactions; Societal impacts & focus for outreach efforts.

Format: Plenary discussion

1100: Wrap-Up Session.

Topics: "White Paper" timetable; post-workshop communications; next steps in planning and organization; feedback from the OOI program

1200: Workshop Ends (General Participants)

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1300: Executive Committee Meeting (Organizers, NSF representatives)

Main tasks: Outline "White Paper"; further define plan follow-up communications with participants and input from community; assign writing tasks; initial review of workshop process.

1500: End of Executive Meeting

Appendix B- Participants

Pierre Lermusiaux	Massachusetts Institute of Technology
R. W. (Wally) Fulweiler	Boston University
Vitalii Sheremet	University of Rhode Island
Jim O'Donnell	University of Connecticut
Joe Salisbury	University of New Hampshire
Nick Nidzieko	Horn Point Lab-University of Maryland
Larry Atkinson	Old Dominion University
Jim Bisagni	University of Massachusetts-Dartmouth
Wendell Brown	Mid-Atlantic Regional Association of Coastal Observing Systems/University of Massachusetts-Dartmouth
Ru Morrison	Northeastern Regional Association of Coastal Observing Systems
Heidi Sosik	Woods Hole Oceanographic Institution
John Goff	University of Texas
John Wilkin	Rutgers University
Scott Glenn	Rutgers University
Martial Taillefert	Georgia Institute of Technology
Steve Lohrenz	University of Southern Mississippi
Mingshun Jiang	University of Massachusetts-Boston
Francisco Chavez	MBARI / OOI Program Advisory Committee
John Morrison	University of North Carolina-Wilmington
Tom Grothues	Rutgers University-Tuckerton Field Station
Erin LaBrecque	Duke University
Dan Brothers	USGS Woods Hole
Mohsen Badiey	University of Delaware
Charlie Flagg	Stony Brook University
Collin Roesler	Bowdoin College
Bill Boicourt	University of Maryland, Center for Environmental Science/OOI Program Advisory Committee
Glen Gawarkiewicz	Woods Hole Oceanographic Institution
Jim Nelson	Skidaway Institute of Oceanography
Ruoying He	North Carolina State University
Jean McGovern	National Science Foundation
Eric Itsweire	National Science Foundation
Al Plueddemann	Project Scientist, Pioneer Array (OOI Implementation Organization) /Woods Hole Oceanographic Institution
Sheri White	Engineer, OOI
Bill Bergen	CyberInfrastructure Team, OOI
Lorraine Brasseur	Ocean Observing Programs, Consortium for Ocean Leadership

Appendix C- Scientists Submitting Statements of Interest

James Bisagni - University of Massachusetts-Dartmouth

Elizabeth North - University of Maryland Center for Estuarine and Environmental Studies

Meng Zhou, Robert Chen, Ron Etter, Robyn Hannigan, Mingshun Jiang, Curtis Olson, Xuchen Wang - University of Massachusetts-Boston

Gareth Lawson, Peter Wiebe, Zhaohui (Aleck) Wang, Donglai Gong, Emily Shroyer - Woods Hole Oceanographic Institution

Tracey Sutton - Virginia Institute of Marine Science

Emmanuel Boss - University of Maine

Burke Hales - Oregon State University

John Goff, James Austin, Mead Allison - University of Texas-Austin

Jon Hare - National Marine Fisheries Service

Dan Codiga - University of Rhode Island