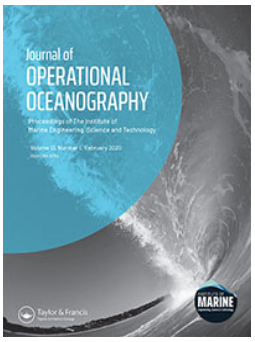


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# Scientific rationale and conceptual design of a process-oriented shelfbreak observatory: the OOI Pioneer Array

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**ABSTRACT**
The Ocean Observatories Initiative (OOI) of the National Science Foundation in the USA includes a coastal observatory called the OOI Pioneer Array, which is focused on understanding shelf/slope exchange processes. The OOI Pioneer Array has been designed and constructed and is currently in operation. In order to fully understand the design principles and constraints, we first describe the basic exchange processes and review prior experiments in the region. Emphasis is placed on the space and time scales of important exchange processes such as frontal meandering and warm core ring interactions with the Shelfbreak Front, the dominant sources of variability in the region. The three major components of the Pioneer Array are then described, including preliminary data from the underwater gliders and Autonomous Underwater Vehicle (AUV) deployments. The relevance of the Pioneer Array to important recent scientific issues in the area, including enhanced warming of the continental shelf and increasing frequency and spatial extent of Gulf Stream interactions with the continental shelf is discussed. Finally, similar observatories in Asia are briefly described, and general conclusions regarding principles that should guide the design of shelfbreak observatories in other geographic regions are presented.

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**KEYWORDS**
Coastal observatories; continental shelf and slope processes; ocean observatory Initiative

## 1. Introduction

The coastal ocean is a complex environment subject to many different forcing mechanisms on multiple space and time scales. Processes vary on scales from metres to hundreds of kilometres, while forcing mechanisms range from large scale weather systems to offshore eddies of order 10–100 km, to estuarine and river plumes that may vary in cross-shelf extent by tens of kilometres in a matter of days. This wide range of space and time scales makes sampling the coastal ocean a very difficult proposition. While sampling strategies all depend critically on the specific science questions, the challenge of making measurements in the coastal ocean typically involves resolving upstream alongshelf flows, determining cross-shelf fluxes from coastal and offshore boundaries, and monitoring air–sea fluxes where coastal orography may significantly affect wind patterns.

The National Science Foundation (NSF) of the United States of America initiated a programme in 2004, the Ocean Observatories Initiative, for long-term observations in several different geographical locations that featured an open competition for conceptual designs for ocean observatories that would answer critical science questions for the coastal and deep ocean. A description of the programme is on the web at http://oceanobservatories.org. Two observatories were selected for the coastal ocean, the Endurance Array in the Pacific Northwest featuring cabled moorings and gliders, and the Pioneer Array south of New England, a process-oriented observatory to study shelfbreak processes and shelf-deep ocean exchange. The Pioneer Array is designed to be relocatable to study processes in different coastal geographical regions; the NSF envisions a competitive process every five years to identify a new region. The science plans for OOI appeared in 2007 (http://oceanobservatories.org/files/Science_Prospectus_2007-10-10_lowres_0.pdf) and a workshop report discussing science themes and operational issues for the Pioneer Array appeared in August, 2011 (http://www.unols.org/sites/default/files/Shelf_Slope_Processes_OOI_Pioneer_Array_2011.pdf).

The geographic position of the Pioneer Array is at the edge of the continental shelf south of New England in the northeast United States (Figure 1). There are three primary components to the Array: moorings, underwater gliders, and Autonomous Underwater Vehicles (AUVs). The primary scientific goal of the observatory is to resolve shelfbreak exchange processes, thus improving understanding

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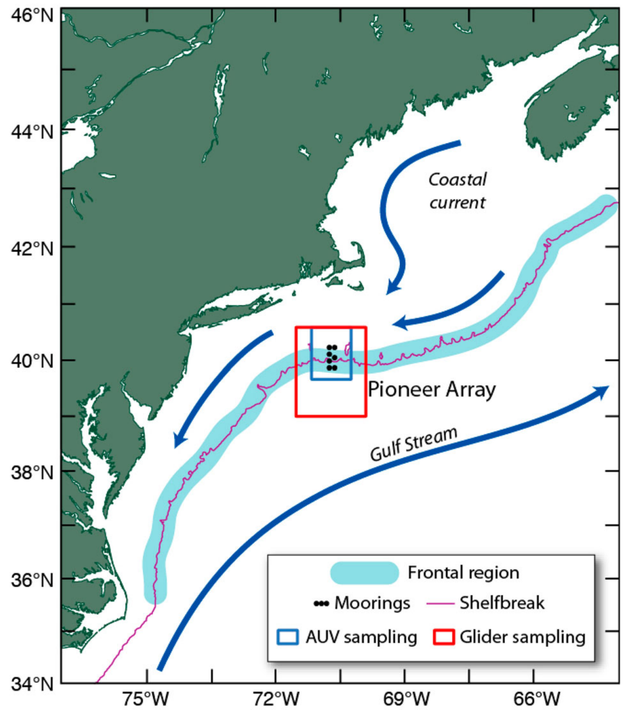



**Figure 1.** Schematic diagram of the continental shelf from Nova Scotia to Cape Hatteras. The coastal current brings relatively cold, fresh water from the north along the shelf. The shelfbreak front extends from the southern flank of Georges Bank to Cape Hatteras and separates the shelf from the warmer, saltier waters offshore. Gulf Stream meanders and eddies create a complex environment over the continental slope to the south of the front. The OOI Pioneer Array, centred on the front south of Cape Cod, includes a moored array (black dots) and operation areas for AUVs (blue) and gliders (red). (Illustration by Jack Cook)

Array, including interactions with the commercial fishing industry that determined the mooring configuration and mobile asset sampling patterns. Similarly, recent issues within the commercial fishing industry in New England have highlighted the societal needs that the OOI Pioneer Array addresses, particularly in understanding the year to year differences in the seasonal evolution of the temperature field and its impact on the continental shelf ecosystem. This paper addresses the factors which determined important aspects of the OOI Pioneer Array design, briefly updates recent trends in the oceanographic conditions in the northeast to show how the science this observatory addresses will help in

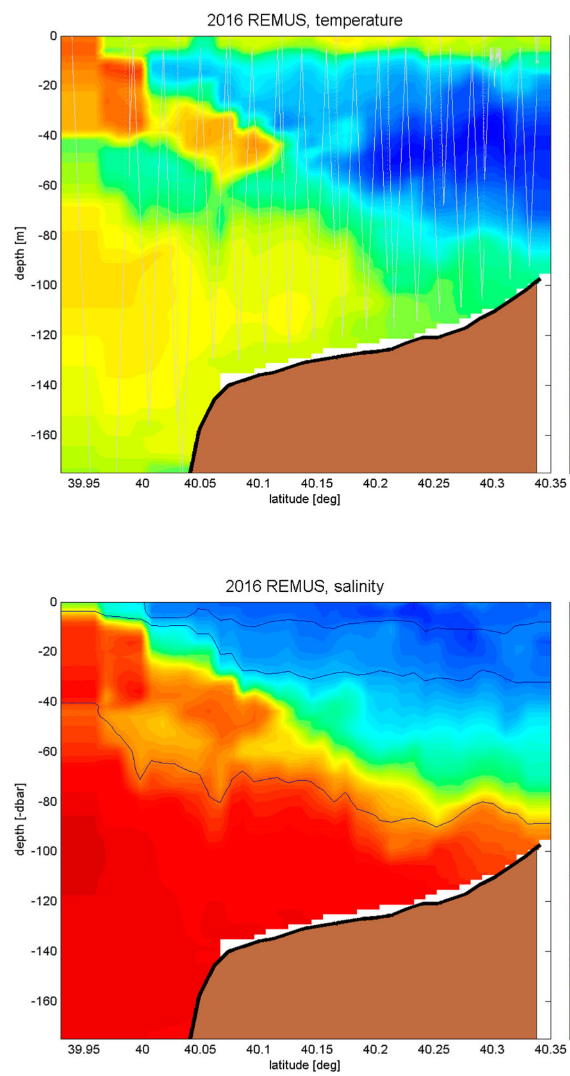



**Figure 2.** Cross-shelf transects of temperature (upper) and salinity (lower) obtained from a Pioneer Array AUV operated on 26 May 2016. The transect extends from the Offshore (left) to Inshore (right) boundaries of the Pioneer moored array, along the Upstream line. The vehicle track (thin lines) is overlaid on the temperature transect. The Shelfbreak Front is near the 10°C isotherm/34.5 isohaline, with the foot of the front just onshore of the northern end of the transect.

of onshore motions of continental slope water masses and offshore motions of continental shelf water masses. The location was carefully chosen in order to minimise influences from canyon bathymetry, estuarine outflows, and processes affected by close proximity to the Gulf Stream.

The three components of the Pioneer Array provide complementary capabilities that allow this observatory to resolve multiple scales of motions. The moorings, located between the 95 and 450 m isobaths (Figure 2), provide temporal information about surface forcing and the vertical structure of the water column. For example, surface buoys at three sites measure meteorological variables necessary to estimate air–sea fluxes using bulk formulae, and wire-following profilers at seven sites provide water column variables from 28 m below the surface to 28 m above the bottom. The moorings are supplemented by a fleet of six gliders that sample the continental shelf, shelfbreak frontal region, and continental slope. High-resolution hydrographic transects are also periodically performed by AUVs to resolve frontal structure.

In this paper, we present a detailed discussion of the scientific rationale for the design of the OOI Pioneer increasingly pressing societal problems, and describes in a systematic way how one should design a shelfbreak observatory that can be adapted for other regions of the world to resolve the important processes and scales to be addressed.

The outline of this paper is as follows. Section 2 covers the scientific rationale for a shelfbreak observatory and discusses historical observations with an emphasis on scales of motions for various processes that affected the design of the Pioneer Array. The scientific objectives and tools of prior experiments in the region are presented along with their comparative strengths and weaknesses in terms of resolving spatial and temporal scales. Section 3 consists of a discussion of the observatory design, including a description of the various platform and sensor types, and the sampling patterns of the mobile assets. Examples of important recent science issues in the shelf/slope region of the northeastern U.S. appear in Section 4, highlighting extreme events such as the widespread warming in 2012 as well as the recent accelerated warming of the continental shelf in the Gulf of Maine and the Middle Atlantic Bight. A brief summary and conclusions appear in Section 5.

## 2. Scientific rationale and historical observations Driving the Pioneer Array design

### *2.1. The shelfbreak front and shelfbreak exchange processes*

The primary oceanographic feature within the OOI Pioneer Array region is the Shelfbreak Front. The front divides relatively cooler, fresher waters of the continental shelf from warm, saltier waters of the continental slope. The front extends from the southern flank of Georges Bank to Cape Hatteras (Figure 1), where the continental shelf waters move offshore and are entrained into the Gulf Stream. A hydrographic section across the front sampled with a REMUS 600 AUV in May 2016, appears in Figure 2. The cross-shelf scale of the front is typically 50 km with the bottom outcrop of the front (also called the foot of the Shelfbreak Front) near the 100 m isobath. The Shelfbreak Jet, associated with the front, is generally 20–40 cm/s but at times, due to wind forcing or Warm Core Ring interactions, may accelerate to as much as 80 cm/s. The Shelfbreak Jet is typically located over the upper continental slope near the 145 m isobath but may be diverted shoreward by winds or warm core ring interaction. A bi-monthly climatology of the front based on bin-averaging by water depth appears in Linder and Gawarkiewicz (1998); they describe characteristics of the Shelfbreak Jet including width, vertical scale, and the isobaths at which the jet core is centred. This was updated using a cross-shelf coordinate based on distance to the shelfbreak, defined as the 100 m isobath (Linder et al., 2006). A further climatological effort, concentrating on summer sections and using streamwise coordinate averaging, appears in Fratantoni and Pickart (2007). Zhang et al. (2011) used climatological density and seasonally averaged wind forcing fields to obtain both the alongshelf and cross-shelf seasonal and annual mean flows across the shelf and slope including the Shelfbreak Jet. More recently, a three-dimensional climatology of the continental shelf in the entire Middle Atlantic Bight appears in the Ph.D. thesis of Naomi Fleming from Rutgers University (Fleming, 2016).

A review of shelfbreak exchange processes appears in the Workshop Report and multiple processes are depicted schematically in Figure 3. Three key processes are: warm core ring interactions (e.g. Bisagni, 1983; Gawarkiewicz et al., 2001; Cenedese et al., 2013), frontal instabilities (Garvine et al., 1988; Gawarkiewicz, 1991; Lozier et al., 2002; Gawarkiewicz et al., 2004; Zhang and Gawarkiewicz, 2015a), and wind forcing (Houghton et al., 1988; Lentz, 2003; Castelao et al., 2008; Siedlecki et al., 2011). A net annual salt flux was estimated by Lentz (2010) by balancing surface and lateral (coastal) inputs with a necessary onshore salt flux to match the observed alongshelf evolution of the salinity field along the 70 m isobath. The number obtained, 0.7 $kg/m^2s^2$, is very similar to the value directly observed by Gawarkiewicz et al. (2004). This is an indication that frontal instabilities may be a dominant process in the annual averaged exchange of salt across the shelfbreak. During spring and summer, mid-depth saline intrusions are commonly observed (Lentz, 2003). In general, shelfbreak exchange processes occur over relatively short spatial scales, 10-40 km, and over time scales ranging from days to weeks. Numerical modelling of shelfbreak exchange has shown, for example, that warm core rings may, in roughly a week, generate as much exchange as normally occurs over three months (Chen, He, et al., 2014). Similarly, numerical models have been useful in establishing alongshelf variations in net transport onto and off of the continental shelf (Chen and He, 2010). It is important to note that the estimates of shelfbreak exchange in Chen and He (2010) show that the standard deviation of net transport on and off the shelf is much larger than the annual mean values. This is why repeated high-resolution observations of an extended duration are so important.

The Shelfbreak Front has long been identified as an area of high productivity (e.g. Marra et al., 1990; Ryan, Yoder, Cornillon, 1999; Ryan, Yoder, Barth, 1999). Recent high-resolution field observations (Hales et al.,

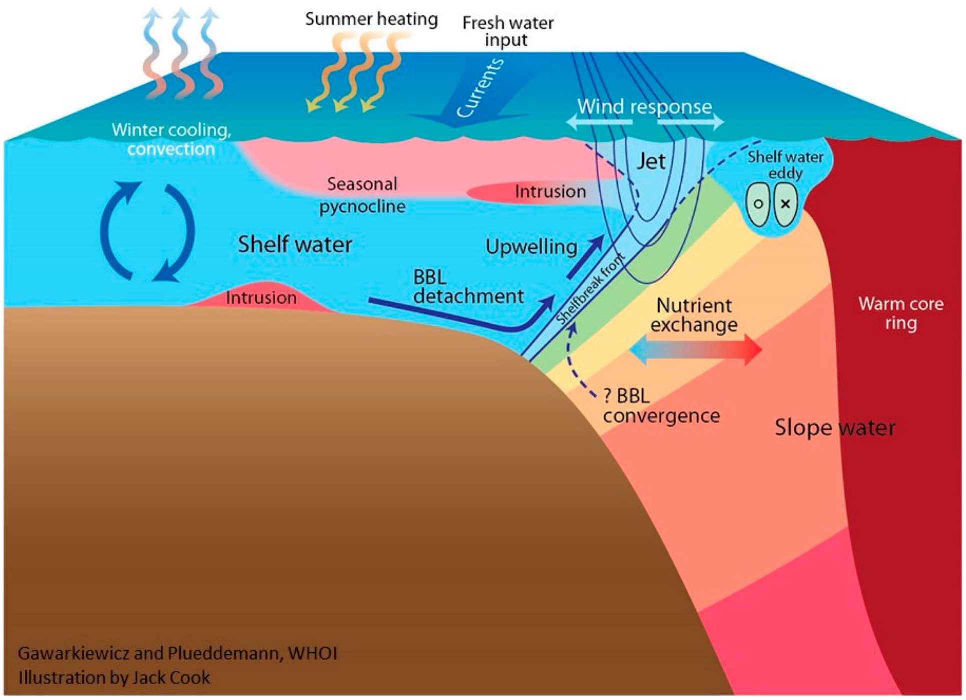



**Figure 3.** A schematic showing important shelfbreak exchange processes. Processes occur throughout the water column and are strongly affected by seasonal stratification. (Illustration by Jack Cook)

2010) used a towed vehicle to map temperature, salinity, and nutrient fields. Estimates of turbulent fluxes of nutrients from the underlying waters were obtained, but there was no evidence from these observations of frontal enhancements observed in previous studies. However, numerical modelling of the shelf and slope have indicated the importance of the frontal upwelling (He et al., 2011) as well as the importance of zooplankton grazing in order to match seasonal means of chlorophyll distributions from ocean colour satellites (Zhang et al., 2013). Regional modelling of nutrients (e.g. Fennel et al., 2006) and carbon cycling (Hofmann et al., 2011) over the continental shelf and slope have also been reported.

## 2.2. Recent inter-annual variability of the continental shelf and slope circulation south of New England

The continental shelf and slope region of the northeastern U.S. has been undergoing dramatic inter-annual variability, particularly in terms of shelf temperatures. The long term temperature trend for sea surface temperature at Nantucket Shoals in the Middle Atlantic Bight, taken from lighthouse daily measurements from 1880-2007, is 0.7 ± 0.3°C per century (Shearman and Lentz, 2010). More recently, however, the warming rate for sea surface temperature has increased on a decadal time scale (Mills et al., 2013; Pershing et al., 2015). Observations from the New Jersey shelf taken from a Ship of Opportunity, the MV Oleander, indicate a much more rapid warming of 0.11 ± 0.02°C per year between 2002 and 2013 (Forsyth et al., 2015). The Oleander observations, obtained from Expendable Bathythermographs over a 37 year time period (1977-2013), confirm that the warming has increased temperatures over the entire water column and not merely in the near surface layer. In addition, it appears that much of the warming over the New Jersey shelf from 2002–2013 occurred near the shelfbreak, and thus may relate to onshore displacements of the Shelfbreak Front. This reinforces the need to understand shelfbreak exchange given the remarkable warming rate evident since 2002.

The year 2012 was an extreme event in terms of recent warming. Mills et al. (2013) reported on the impacts of the 2012 warming on both sea surface temperature extremes as well as the implications for fisheries management. Further discussion of the implications of warming on Atlantic Cod appear in Pershing et al. (2015). Chen, Gawarkiewicz, et al. (2014) examined buoy data as well as Oleander XBT data from 2012 to determine the forcing mechanism leading to the extreme temperatures in the first six months of the year. They found that a simple one-dimensional heat balance accounted for the temperature anomalies, and thus that air–sea flux anomalies were the primary cause of the extreme warming in 2012. Chen et al. (2015) used a numerical model to confirm that the temperature anomalies from 2012 were indeed primarily due to air–sea flux anomalies. Alongshelf advection over the continental shelf actually contributed cooling of the continental shelf in the first six months of 2012, thus emphasising the role of the meteorological forcing in producing record warm conditions.

The air–sea flux anomalies in turn related to a ridge of the Jet Stream persisting in a northward position through much of the winter in early 2012. This may relate to the influence of Arctic Amplification on the Jet Stream (Francis and Vavrus, 2012). The Jet Stream has recently developed more frequent High Amplitude Patterns (Francis and Skific 2015), and further analysis of the waviness of the Jet Stream in mid-latititudes confirms the influence of Arctic Amplification (Francis and Vavrus, 2015). While arguments continue over the causes of the recent changes in the Jet Stream (e.g. Hassanzadeh et al., 2014), changes in Jet Stream dynamics and patterns lead directly to changing the seasonal patterns and annual extremes of temperature over the continental shelf in the vicinity of the Pioneer Array. The changes in shelf temperature in turn affect cross-frontal temperature and density gradients that must in turn modify rates of shelfbreak exchange.

## 3. Design of a process-oriented shelfbreak observatory

In this section we briefly review previous experiments south of New England and then discuss the rationale behind the design of the three major components of the Pioneer Array: moorings, gliders, and AUVs. The design of the mooring array, in particular, evolved as a result of meetings between scientists and representatives of the commercial fishing industry active in the region. We discuss the process involved as well as the suggestions received from the industry representatives that were eventually incorporated in the design. An important aspect of any scientific observations in shelfbreak regions is elevated levels of fishing activity, and so this is an issue that is likely to recur in other geographic regions as shelfbreak observatories are built around the world.

### 3.1. Previous experiments at the shelfbreak south of New England

The continental shelf and shelfbreak region south of New England have been the setting for a number of observational programmes since the 1970s. It is instructive to briefly describe these experiments and how they differ from the Pioneer Array. For example, because of new technologies, the Pioneer Array is able to obtain both extended duration and high-resolution measurements of traditional hydrographic fields as well as other important variables such as chlorophyll *a* fluorescence, oxygen, nitrate, and $pCO_2$. By way of contrast, previous experiments were either of long duration but limited spatial resolution (with mooring arrays), or high spatial resolution but limited duration (e.g. with towed vehicles).

The first mooring array that resolved the continental shelf and shelfbreak flows was the Nantucket Shoals Flux Experiment (NSFE) in 1979. The primary goal of the array was to resolve the alongshelf transport over the continental shelf. The moorings spanned the 40 m to 810 m isobaths (Figure 4). The NSFE six mooring line-array had an average spatial separation of 19 km. The array was able to obtain an annual averaged alongshelf transport of $0.38 \pm 0.07$ Sverdrups ($10^6$ $m^3/s$) between the 40 and 120 m isobaths (Beardsley et al., 1985). In addition to the mooring array, periodic cross-shelf hydrographic sampling occurred on roughly monthly time scales (Brown et al., 1985). A limitation of the mooring array was the lack of conductivity sensors, so that the variability of the salinity (and density) field could not be determined.

The Shelf Edge Exchange Processes (SEEP-I) experiment occurred in 1983-1984. This experiment was focused on determining the offshore transport of organic carbon, carbonate, and particulate iron from the continental shelf to the continental slope (Walsh et al., 1988). A mooring array was oriented cross-shelf between the 80 m and 2000m isobaths (Figure 4). The SEEP-I five mooring line-array on the shelf and slope had spatial separation of 15–20 km. Results indicated that this region had a minimal export of particles from the continental shelf to the continental slope, with much of the particles carried alongshelf towards Cape Hatteras or else being deposited over the continental shelf. Only 20% to 60% of the organic debris from the continental shelf crossed the shelfbreak in the SEEP-I region.

An important result from the SEEP-I programme was resolving seasonal differences in the nature of the variability of the Shelfbreak Front. Houghton et al. (1988) found that the Shelfbreak Front had significant variability in the 1–3 d synoptic band in winter, with cross-shelf motions on the order of 10–20 km. However, the cross-shelf velocity was in quadrature with temperature, resulting in large fluctuations but essentially a zero mean for the eddy heat flux. In contrast, during the summer, the front had instabilities that led to enhanced cross-shelf heat flux beneath the base of the seasonal thermocline.

Frontal instabilities were studied by Garvine et al. (1988) using high resolution hydrographic surveys and surface drifters. They found large amplitude frontal meanders with a wavelength of 25 km, a period of four days and a westward phase speed of 11 cm/s. While

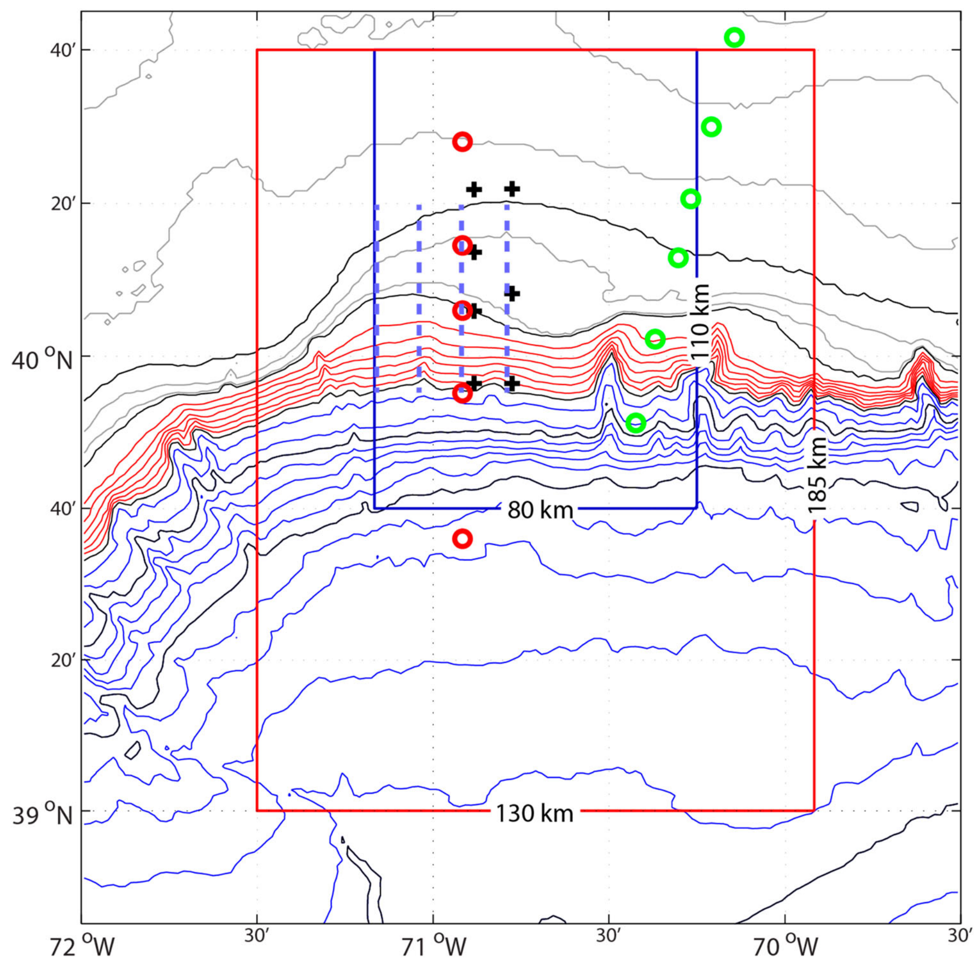



**Figure 4.** Plan view of the Pioneer Array region. The Pioneer moored array is denoted by black crosses. The blue rectangle denotes the AUV operations area and the red rectangle denotes the glider operations area. The locations of observations from prior experiments are also shown, including NSFE moorings (green circles), SEEP-1 moorings (red circles), and Shelfbreak PRIMER towed vehicle transects (light blue dashed lines). Bathymetry contours are at 10 m (gray), 50 m (red) and 100 m (blue) intervals, with 100, 150, 500, 1000 m and 2000m contours in black.

able to resolve the nature of the backwards breaking frontal waves and Lagrangian aspects of the flow field (Garvine et al., 1989), the eddy heat flux was in the opposite direction of that anticipated from the mean thermal field. The general characteristics of the unstable waves were studied using a three layer semi-geostrophic analytical model by Gawarkiewicz (1991). While this study was able to resolve the frontal waves, the shipboard effort duration was only three weeks, in contrast to the year long mooring deployments from the Nantucket Shoals Flux Experiment and SEEP-I.

### *3.2. Spatial and temporal scales of variability in the shelfbreak region*

For the design of the OOI Pioneer Array, it was critical to establish the expected spatial and temporal scales of variability within the shelfbreak region. A key process expected to substantially contribute to the variability within the Shelfbreak Front is frontal instability. This was initially examined by Flagg and Beardsley (1978) who used a two-layer model to examine frontal motions in winter. They found a dominant wavelength of 80 km with periods of roughly 5 days from a linear stability analysis. The model's most unstable wavelength was consistent with observations from a synoptic hydrographic survey. Garvine et al. (1988) did repeated synoptic CTD surveys during summer and found large amplitude unstable frontal waves with a wavelength of 25 km. A three-layer stability model (which included an upper layer similar to the observed summer conditions) produced unstable waves within the 20-40 km range of wavelengths consistent with the observations (Gawarkiewicz, 1991). A more complex stability analysis was conducted by Lozier et al. (2002) using continuous stratification and a Gaussian jet. The Shelfbreak Front was unstable over a wide range of wavelengths extending to the shortest wavelengths resolvable (just under

10 km). There was not a clearly defined most unstable wavelength. The energetics of the instability were examined, and the instabilities were primarily baroclinic, with energy transfers primarily occurring within the upper 50 m of the water column.

Observationally, frontal waves have been found with wavelengths of between 20 and 80 km. Ramp et al. (1983) measured frontal waves downstream of a warm core ring with a wavelength of 23 km. The most detailed measurements of frontal instabilities within the Shelfbreak Front were made during the Shelfbreak PRIMER experiment (Gawarkiewicz et al., 2004). A large amplitude (30 km peak to trough in the cross-shelf direction) frontal wave was observed with a wavelength of 40 km. This wave had a period of 4 days and a westward propagation speed of 11 cm/s.

In addition to quantifying the frontal wave properties, hydrographic transects obtained with a towed SeaSoar vehicle during Shelfbreak PRIMER (Figure 4) allowed for quantitative analysis of the spatial and temporal decorrelation scales for temperature, salinity, and density fields. Table 1, reproduced from Gawarkiewicz et al. (2004), shows that the spatial decorrelation scales range from 5 km near the surface to 20 km at 100 m depth. For the upper 50 m of the water column, the spatial decorrelation scales vary between 7 and 12 km. The temporal decorrelation scale ranged from 0.8–1.4 days during the week of observations. From the climatology in Linder and Gawarkiewicz (1998), the annual average width of the Shelfbreak Jet in the Nantucket Shoals region south of New England is 21 km. This is an important cross-shelf scale that is necessary to resolve with the mooring array.

The spatial scales of variability were confirmed by Todd et al. (2013) using a four month glider deployment. In addition to confirming an alongshelf scale of 40 km, they also found a cross-shelf scale of roughly 50 km beyond the surface frontal outcrop for the presence of thermohaline anomalies along isopycnals (spice). This can roughly be regarded as a scale for the envelope of meander amplitudes, although other processes such as shelf streamers around warm core rings and frontal excursions due to wind forcing also occurred during the glider deployment.

**Table 1.** Space-time correlation scales.

| Variable | Depth (m) | Along-shelf scale (km) | Cross-shelf scale (km) | Time scale (days) |
|---|---|---|---|---|
| T | 18 | 7 | 9 | 1.5 |
| T | 54 | 7 | 7 | 1.1 |
| S | 18 | 4 | 12 | 1.7 |
| S | 54 | 7 | 8 | 1.1 |
| Density | 18 | 8 | 7 | 1.4 |
| Density | 54 | 20 | 20 | 1.1 |
| U | 18 | 17 | 12 | 0.6 |
| U | 57 | 9 | 9 | 1.0 |
| V | 18 | 8 | 9 | 1.4 |
| V | 57 | 12 | 12 | 1.0 |

Space-time correlation scales in the Pioneer Array region. Along-shelf, cross-shelf and time scales are presented for temperature, salinity density and velocity at various depths.

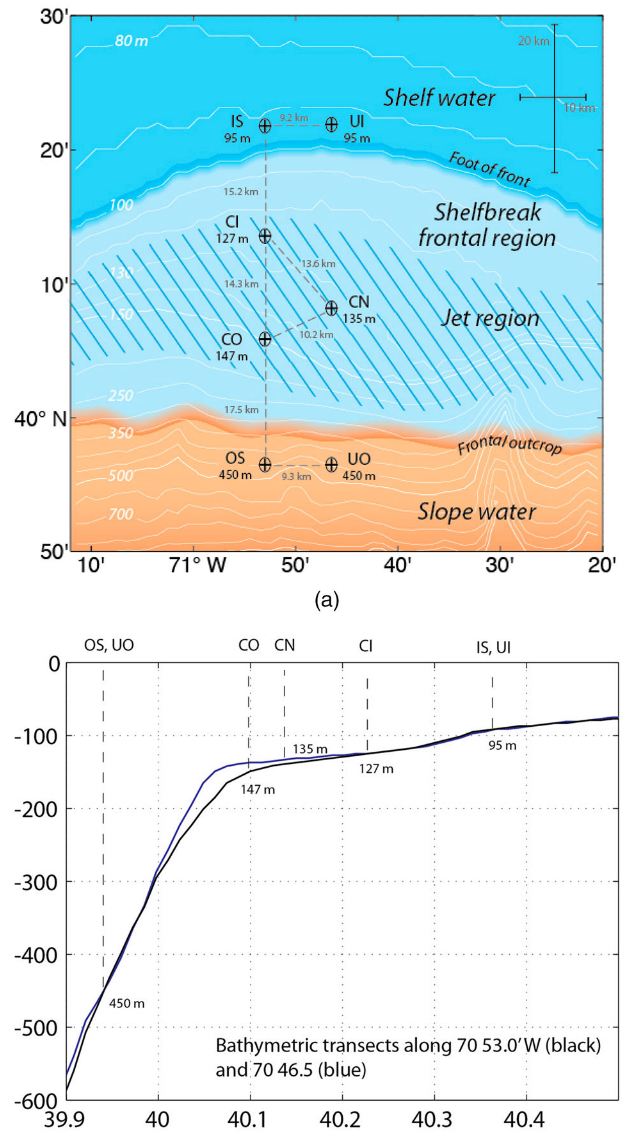
### 3.4. Components and design of the Pioneer Array

The Pioneer Array consists of three major components: moorings, gliders, and AUVs. Each of the components serves a different scientific purpose, while the integrated design allows for both long duration and high resolution observations of the highly variable Shelfbreak Front. The array design was driven by several overarching goals: 1) A region of relatively straight bathymetry, away from complicating factors such as canyons or river outflows, 2) Observations spanning the expected inshore/offshore extent of the front, 3) Resolution of along- and across-shelf spatial scales associated with the frontal system, 4) Allowing for practical constraints like shipping lanes, commercial fishing and cost.

#### 3.4.1. Moored Array

Moorings are necessary to provide time series of important variables at multiple locations across and along the front. The moored array is centred at the shelfbreak roughly 130 km south of Martha's Vineyard (Figure 1), a region with relatively straight bathymetry distant from complicating features such as canyons and river outflows. The moored array consists of two lines running north–south (Figure 5): one along 70° 53' W (western line) and one along 70° 46.5' W (upstream line). The moored array incorporates ten moorings at seven sites – three sites contain a mooring pair (Table 2). The mooring sites are named according to their relative position within the array and referred to by two-letter codes. Locations (Table 2) designate the site centre. Each site has an operating radius of 1 km (Figure 5); all moorings are deployed within the operating radius, typically within 500 m of the centre. Moorings are deployed for approximately 6 months and then recovered for refurbishment; refurbished moorings are deployed at the same site to maintain a continuous time series.

In the Pioneer Array region, the climatological mean position of the foot of the front is near the 100 m isobath (Linder and Gawarkiewicz, 1998). The shallowest mooring sites (IS and UI) are at 95 m depth, just inshore of the mean position of the foot of the front. Thus, these sites are expected to be in shelf water. The upstream site (UI) is 9.2 km away, comparable to the O(10 km) correlation scale of hydrographic features, and thus allowing along-shelf gradients to be estimated. The foot of the front is known to experience cross-shelf excursions from its mean position (e.g. Flagg et al., 2006;



(b)

**Figure 5.** (**a**) Plan view of the moored array locations plotted over bathymetry (white lines) with the shelfbreak front depicted schematically. Mooring sites (crosses) are described in Table 2; circles indicate the 1 km operating radius at each site. Distances between site centres (dashed lines) are noted. The IS and UI sites are typically in Shelf Water, inshore of the foot of the front. The CI, CN and CO sites are within the shelfbreak jet region. The OS and UO sites are typically in Slope Water, offshore of the frontal outcrop. (**b**) Cross section of bathymetry along the two mooring lines with the mooring locations indicated. Note the local 'break' in the bathymetric slope at about 100 m depth as well as the transition from continental shelf to continental slope at about 150 m depth.

Gawarkiewicz et al., 2004) and bottom intrusions of slope water extending tens of kilometres shoreward of the mean position occur periodically (Ullman et al., 2014). However, extending the moored array further inshore was impractical due to the presence of shipping lanes running east–west at approximately 40° 22' N; the shallow sites are only 3 km to the south of the southernmost shipping lane.

**Table 2.** Pioneer moored array.

| Site Code | Site Name | Site Center | Water Depth | Moorings | Mooring Type(s) |
|---|---|---|---|---|---|
| UI | Upstream-Inshore | 40°21.9'N 70°46.5'W | 95 m | 1 | CPM |
| IS | Inshore | 40°21.8'N 70°53.0'W | 95 m | 2 | CSM, CPM* |
| CI | Central-Inshore | 40°13.6'N 70°53.0'W | 127 m | 1 | CPM |
| CN | Central | 40°08.2'N 70°46.5'W | 135 m | 2 | CSM, CPM* |
| CO | Central-Offshore | 40°05.9'N 70°53.0'W | 147 m | 1 | CPM |
| OS | Offshore | 39°56.4'N 70°53.0'W | 450 m | 2 | CSM, CPM |
| UO | Upstream-Offshore | 39°56.4'N 70°46.5'W | 450 m | 1 | CPM |

Pioneer moored array description by site. The site codes and names are given along with the location and water depth. Sites are occupied by either one or two mooring types. CPMs replaced by a profiling glider in summer are indicated by *.

A central triangle of mooring sites (CI, CN and CO) is meant to resolve the Shelfbreak Jet, expected to be centred over the 120-150 m isobath in the Pioneer Array region. The cross-shelf spacing between the three sites is <10 km, compared to a typical jet width of ~20 km. The CI and CO sites combine with IS and OS to create a cross-shelf line along 70° 53' W with spacing of 13.6–17.5 km. The CN site is along the upstream line at 135 m depth, where the Shelfbreak Front will typically be encountered near the middle of the water column (cf. Figure 2).

The deepest mooring sites (OS and UO) are at 450 m depth, approximately 45 km offshore of the 100 m isobath and seaward of the mean position of the Shelfbreak Jet. Thus, these sites are expected to be in slope water. However, as shown by Linder et al. (2006), the front may stretch as much as 80 km offshore of the 100 m isobath. Additionally, streamers of shelf water (e.g. due to encounters with warm core rings; Cenedese et al., 2013) may extend as far south as the North Wall of the Gulf Stream, well in excess of 100 km south of the shelfbreak. However, occupying additional deep water sites was not possible within the financial constraints of the programme.

The result is a moored array with a cross-shelf span of 47 km, commensurate with the typical cross-shelf scale of the front (Figure 3), and inter-mooring distances that are capable of resolving the Shelfbreak Jet. The mobile assets, the gliders and AUVs, provide the high spatial resolution necessary to resolve motions on scales smaller than the baroclinic Rossby radius (order 5-10 km in this region).

The asymmetric array with unequal spacing between mooring sites (Figure 5) may seem unusual, and indeed the initial moored array design envisioned a symmetric array with cross-shelf and along-shelf spacing of ~10 km. The final array design resulted from discussions with the commercial fishing industry during a series of meetings held in the fall of 2011 (Appendix 1). In the course of the discussions, numerous recommendations were made to modify equipment and operational procedures to maximise safety and minimise the risk of undesired interactions between fishing activities and the Pioneer Array infrastructure. Perhaps the most important result was a change to the arrangement of the mooring sites. The initial design envisioned an equally-spaced line-array of five moorings along 70° 48’ W plus two upstream sites. However, the fishing industry representatives argued persuasively that this did not leave a corridor for fishing vessels to pass through, particularly in the vicinity of the Shelfbreak Jet. An alternate scheme was proposed, in which four of the moorings remained on the western line, but the central mooring shifted east to the upstream line. Additional shifts in the longitude of the two lines, as well as the latitude of several sites, allowed two of the moorings (CN and CO) to be located next to known ‘hangs’, which commercial fishing vessels normally avoid. These changes created a more ‘open’ array and reduced the likelihood of interactions at the CN and CO sites, which are located in an area of high fishing activity.

### 3.4.2. Moored platforms and instrumentation

Ten moorings of two different types are distributed among the seven sites (Table 2). The two mooring types are Coastal Surface Moorings (CSMs) and Coastal Profiler Moorings (CPMs). Three sites, IS, CN and OS, combine CSMs and CPMs to obtain near-surface and near bottom time-series measurements along with periodic vertical profiling of the water column. The remaining sites have CPMs only.

The CSMs (Figure 6) are designed to provide relatively high levels of power from the surface to the seafloor and accommodate a wide variety of fixed-depth instrumentation at surface, near-surface and near-bottom locations. CSM buoys incorporate rechargeable batteries and generate power using solar panels and wind turbines. Electro-mechanical cables and specially designed junctions allow power and data to be transmitted along the mooring line. Electro-mechanical stretch hoses provide compliance. Multi-Function Nodes (MFNs) at the seafloor house instrumentation and an anchor recovery system. Instrumentation is located on the surface buoys, on Near Surface Instrument Frames (NSIFs) at 7 m depth, and on the MFNs at about 1 m off the bottom. CSMs are deployed at

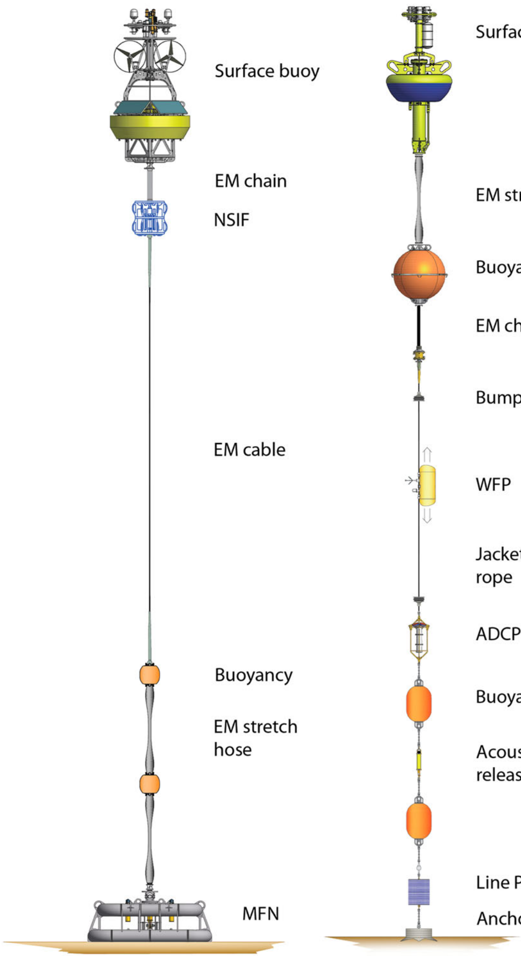



**Figure 6.** Schematic diagrams of the two different mooring types used in the Pioneer Array. Coastal Surface Moorings (CSMs, left) include power generation on the surface buoy, a Near Surface Instrument Frame (NSIF) at 7 m depth, and electro-mechanical (EM) cable and stretch hoses extending to an instrumented anchor frame called a Multi-Function Node (MFN). Coastal Profiler Moorings (CPMs, right) accommodate wire-following profilers and ADCPs. Anchors on both moorings are recoverable.

three sites, IS, CN and OS. All three have a common interdisciplinary sensor suite measuring over 30 variables with 20 instruments of 14 different types (Table 3). The CN buoy adds a second surface meteorology package, a covariance flux package (Edson et al., 1998; Flugge et al., 2016) and surface wave measurements.

The CPMs (Figure 6) are primarily designed to accommodate wire-following profilers, which use a motor drive to cycle instruments up and down the mooring wire (Mathewson and Zani, 2012). CPM buoys do not generate power; all instrumentation runs from primary batteries. In order to avoid vigorous mooring motion due to surface wave orbital velocities, a subsurface buoyancy sphere is placed at 18 m depth. An electro-mechanical stretch hose is used to decouple the sphere from the surface while allowing data transfer via

**Table 3.** CSM core instrumentation.

| Coastal Surface Mooring (CSM) Core Instrumentation | | | | |
|---|---|---|---|---|
| Instrument Series | Code | Measurement(s) | Make/Model | Location(s) |
| Surface Meteorology | METBK | Air temperature, relative humidity, barometric pressure, precipitation, wind speed, wind direction, shortwave radiation, longwave radiation, sea surface temperature, sea surface salinity | Star Engineering ASIMET | buoy tower, buoy base (second system at Central Site only) |
| Covariance Flux | FDCHP | Direct covariance flux (momentum and buoyancy) | WHOI | buoy tower (Central site only) |
| CO2 | PCO2A | Partial pressure CO2 in air, Partial pressure CO2 in water | Pro-Oceanus pCO2 Pro | buoy tower, buoy base |
| Surface Waves | WAVSS | Surface wave statistics and directional properties | Axys Technologies TRIAXYS | buoy hull (Central site only) |
| Fluorometer | FLORT | Chlorophyll-a, CDOM, optical backscatter | Wetlabs ECO-triplet | NSIF |
| Radiometer | SPKIR | Spectral irradiance | Satlantic OCR-507 | NSIF |
| Nutrients | NUTNR | Nitrate concentration | Satlantic ISUS | NSIF |
| Spectro-photometer | OPTAA | Optical absorption and attenuation | WET Labs AC-S | NSIF, MFN |
| CTD | CTDBP | Temperature, conductivity, pressure | Seabird SBE-16+ | NSIF, MFN |
| Oxygen | DOSTA | Dissolved oxygen | Aanderaa Optode 4831 | NSIF, MFN |
| pH | PHSEN | Seawater pH | Sunburst SAMI | NSIF, MFN |
| Velocity | VELPT | Single point water velocity, acoustic backscatter | Nortek Aquadopp | NSIF, MFN |
| CO2 | PCO2W | Partial pressure CO2 in water | Sunburst SAMI | MFN |
| Pressure | PRESF | Seafloor pressure | Seabird SBE-26+ | MFN |
| Velocity profile | ADCPT | Water velocity profile, acoustic backscatter profile | Teledyne RDI Workhorse | MFN |
| Bio-acoustics | ZPLSC | Multi-frequency acoustic backscatter | ASL Environ. Sci. AZFP | MFN |

Coastal Surface Mooring core instrumentation, including the instrument code, measurements made by each instrument series, make and model, and location on the mooring.

telemetry systems to the surface buoy. The mooring design results in an upper limit for the profilers of 23 m below the surface. The constraints of an anchor recovery system and the buoyancy to hold it upright result in a lower limit of 23 m off the bottom. The profilers are programmed to operate within these upper and lower limits, from 28 m below the surface to 28 m above the bottom. The wire-following profilers measure 10 variables with 5 different instruments (Table 4). CPMs that are not co-located with CSMs also include upward looking Acoustic Doppler Current Profilers (ADCPs).

Both CSMs and CPMs are designed with recoverable anchors. The CSM design utilises a flat-plate anchor suspended within the MFN and attached to several hundred metres of synthetic line spooled within a foam buoyancy element. CSM recovery occurs in three stages. First, the MFN is separated from the anchor and the mooring riser is recovered. Next, the buoyancy element is released from the anchor allowing it to rise to the surface while offspooling line. Finally, the anchor is hauled using the synthetic line. The CPM design is similar in concept, but the buoyancy and spooled 'line pack' are separate elements along the mooring line (Figure 6). An acoustic release between upper and lower buoyancy elements allows the mooring riser to be separated and recovered. Another release frees the line pack frame (but not the line) from the anchor. The lower buoyancy element brings the line pack to the surface while line is offspooled.

The OS site is occupied by a CSM/CPM pair. Starting in 2017, the IS and CN sites will be occupied by a CSM/CPM pair in winter and 'profiling gliders' in summer. This approach was the result of the intersection of scientific needs and operational constraints. The original

**Table 4.** CPM core instrumentation.

| Coastal Profiler Mooring (CPM) Core Instrumentation | | | | |
|---|---|---|---|---|
| Instrument Series | Code | Measurement(s) | Make/Model | Location(s) |
| CTD | CTDPF | Temperature, conductivity, pressure | Seabird SBE-52MP | Wire following profiler |
| Oxygen | DOFST | Dissolved oxygen | Seabird SBE-43F | Wire following profiler |
| Fluorometer | FLORT | Chlorophyll-a, CDOM, optical backscatter | Wetlabs ECO-triplet | Wire following profiler |
| Radiometer | PARAD | Photosynthetic available radiation | Biospherical QSP-2200 | Wire following profiler |
| Velocity | VEL3D | Single point water velocity, acoustic backscatter | Nortek Aquadopp II | Wire following profiler |
| Velocity profile | ADCPT | Water velocity profile, acoustic backscatter profile | Teledyne RDI Workhorse | Mooring line |

Coastal Profiler Mooring core instrumentation, including the instrument code, measurements made by each instrument series, make and model, and location on the mooring.

vision was to pair the CSMs with surface-piercing profilers (Sullivan et al., 2010; Barnard et al., 2010) at IS and CN to provide high-resolution profiles throughout the water column. However, the systems developed for OOI experienced a variety of environmental, engineering and control system challenges in their initial Pioneer Array deployments. A decision was made to transition to the more robust CPMs. However, the upper profiling limit of the CPMs means that they will not resolve near-surface stratification in spring and summer. Gliders were seen as a way to provide 'virtual moorings' with the desired vertical resolution near the surface. Gliders can hold station within a few kilometres in modest currents (e.g. up to 0.25 m/s) while making repeated dives. Power constraints preclude having the science sensors running for all dives; measurements every 5th dive would provide about 10 profiles per day at the shallow mooring sites. In winter, the CPM upper profiling limit does not significantly compromise the science goals (since the upper ocean tends to be well mixed), and gliders are less effective as virtual moorings because they may be blown off course by strong winds and currents associated with winter storms.

Multiple, networked microprocessors on the moorings control power, instrument data flow, and multiple telemetry systems. The CSMs have microprocessors in the buoy, NSIF and MFN and communications along the mooring line are by Ethernet and serial communications. The CPMs have microprocessors in the buoy and communications along the mooring line are by inductive telemetry. Both CSM and CPM buoys house three different telemetry systems (Iridium, Freewave and Wi-Fi) to allow not only data delivery, but also command and control from shore or a nearby ship. CSM buoys include a fourth system (Fleet Broadband) to accommodate higher data rates.

### 3.4.3. Gliders and AUVs

A novel element of the Pioneer Array design is the integration of mobile platforms (gliders and AUVs) with the moored array. Six Slocum gliders (Teledyne-Webb Research) were planned for deployment within the glider operations area (Figure 4). All of the glider hulls are rated to 1000 m depth. Four gliders outfitted with 1000 m buoyancy engines provide deep profiling over the continental slope. Two gliders are outfitted with a 200 m buoyancy engine to provide higher efficiency in shallow waters on the shelf. The six 'track line following' gliders measure the same 10 variables as the CPMs using 5 different instruments (Table 5). Instruments are usually operated during the dive only and, due to power constraints, the velocity profiler is typically operated every fourth dive. This may have implications for analysis of oxygen data on the gliders as, due to hysteresis effects, it is common practice to empirically regress lag coefficients to minimise differences between ascent and descent (e.g. Bittig et al., 2014). The instrumentation on the profiling gliders differs from that on the track-line gliders (Table 5) – the current profiler is replaced by a second fluorometer and a nitrate sensor.

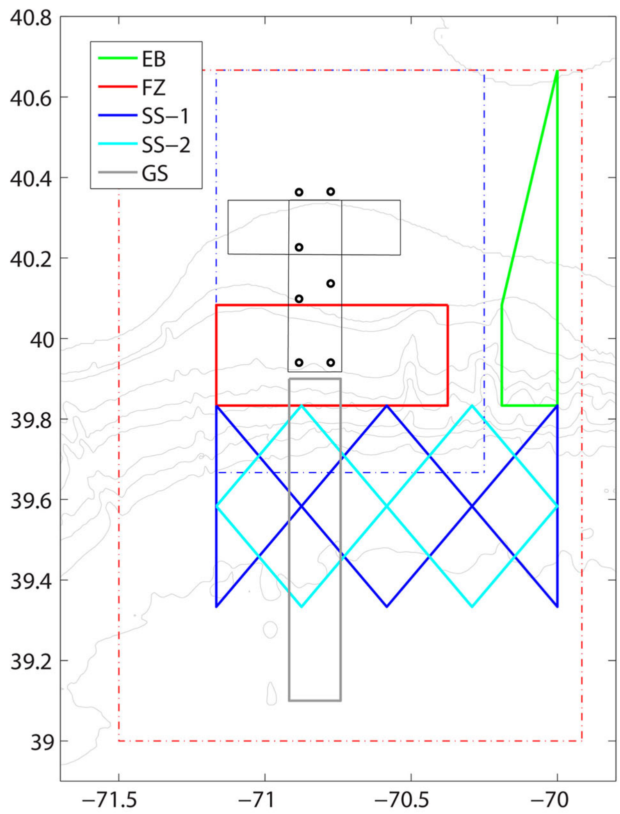
Gliders travel horizontally about five times their dive depth, so operating on the shelf (water depth <=200 m) gliders provide along-track horizontal resolution of order 1 km. The gliders have nominal endurance of 90 days, after which they are recovered for refurbishment and battery replacement. A newly refurbished glider is deployed on the same line. Thus, it requires 12 gliders to sustain a 6 glider fleet in the water. In fact, due to difficulties in meeting a 90 d turnaround time for gliders that may need substantial refurbishment or repair after recovery, it has been difficult to keep more than 4–5 gliders in the water at a time.

The scientific objectives of the glider operations fall into three main categories: providing upstream boundary conditions for numerical modelling of the shelf flow, observing alongfront variability and scales of motions in the frontal region, and resolving the structure of circulation features over the continental slope, such as Warm Core Rings and smaller slope eddies that provide offshore forcing to the front. These objectives are met using 5 track lines (Figure 7(a)). The Eastern Boundary

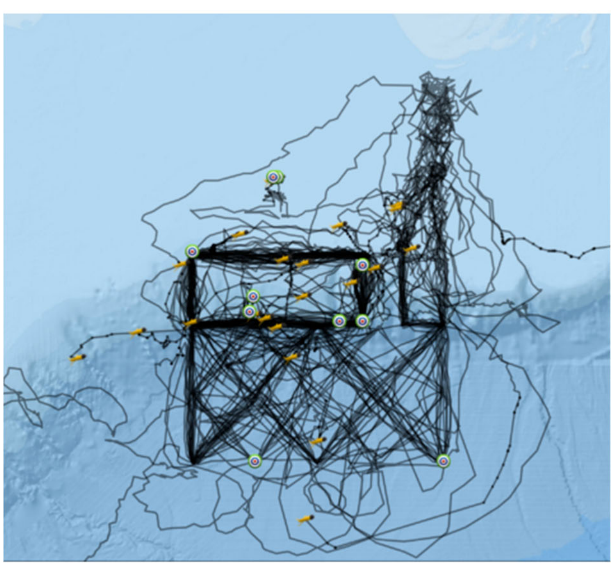
**Table 5.** Glider and AUV core instrumentation.

| Glider and AUV Core Instrumentation | | | | |
|---|---|---|---|---|
| Instrument Series | Code | Measurement(s) | Make/Model | Location (s) |
| CTD | CTDGV, CTDAV | Temperature, conductivity, pressure | Seabird CTD-GP | Glider, AUV |
| Oxygen | DOSTA | Dissolved oxygen | Aanderaa Optode 4831 | Glider, AUV |
| Fluorometer | FLORT | Chlorophyll-a, CDOM, optical backscatter | Wetlabs ECO-triplet | Glider, AUV |
| Radiometer | PARAD | Photosynthetic available radiation | Biospherical QSP-2150 | Glider, AUV |
| Velocity profile | ADCPA | Water velocity profile, acoustic backscatter profile | Teledyne RDI Explorer DVL | Track-line Glider |
| Fluorometer | FLORT | Three-channel optical backscatter | Wetlabs ECO-triplet | Profiling Glider |
| Nutrients | NUTNR | Nitrate concentration | Satlantic SUNA | Profiling Glider, AUV |
| Velocity profile | ADCPA | Water velocity profile, acoustic backscatter profile (up & down looking) | Teledyne RDI Workhorse | AUV |

Glider and AUV core instrumentation, including the instrument code, measurements made by each instrument series, make and model, and platform location. A location designation of 'glider' means the instrument is on all gliders. Some instruments are found only on track-line following gliders, profiling gliders or AUVs.




(a)



(b)

**Figure 7.** (**a**) Planned track lines for the two Pioneer Array AUVs (thin black lines) and the six Pioneer Array gliders. One glider is assigned to each of the Eastern Boundary (EB), Slope Sea 1 (SS-1), Slope Sea 2 (SS-2) and Gulf Stream (GS) lines. Two gliders are assigned to the Frontal Zone (FZ) line. The boundaries of the AUV (blue dashed) and glider (red dashed) operation areas are shown for reference. (**b**) A composite of actual glider trajectories for the first two years of operations. Note that the GS line (Figure 7a) was not occupied during this period.

(EB) line is intended to provide upstream conditions for shelf flows. This line is roughly 200 km long and can be completed in about a week. A 200 m engine glider is assigned to this line, which is mostly in water less than 250 m deep. The Frontal Zone (FZ) line is intended to sample along the front. The FZ line is about 200 km long and can be completed by one glider in about a week. This line is occupied by two gliders, one with a 200 m engine and one with a 1000 m engine, to provide a nominal repeat sampling time of 3–4 days, a closer match to the time scale of frontal variability. There are two Slope Sea (SS) lines with intersecting diagonal tracks that create a 'diamond' pattern intended to resolve mesoscale features in the slope sea. These lines are 300-400 km long and will take about two weeks to complete. One 1000 m glider is dedicated to each track. The Gulf Stream (GS) line is intended to extend the southern limit of sampling towards the north wall of the Gulf Stream, sampling nearer to the 'source water' of eddies and meanders that may impinge on the frontal region. The GS line is 200 m long, can be completed in about a week, and is occupied by a 1000 m glider.

A composite of actual glider trajectories from the first two years of glider operations appears in Figure 7(b). The majority of trajectories follow the planned track lines within a few kilometers. However, at times strong currents (e.g. due to Gulf Stream eddies and meanders or sustained winds during storms) result in excursions away from the planned path. In some cases, gliders were unable to continue along the line due to malfunction and were recovered.

The Pioneer glider data have been used to examine shelfbreak exchange processes. Zhang and Gawarkiewicz (2015b) included Pioneer glider data from the EB line to examine a Warm Core Ring interaction with the front that displaced the front shoreward by 30 km and drove a filament of ring water westward along the shelfbreak. This event, named a Pinocchio's Nose Intrusion by Zhang, led to significant onshore transport of heat and salt. A surprising element of the process was that the ring water extended over the full depth of the water column shoreward of the front. Further details, including the momentum balances and potential vorticity distribution from an idealised numerical model study of the process, are available in the paper.

The AUVs play an important role in the observatory design because they move quickly (e.g. 1.5 m/s) relative to gliders (0.25 m/s) and thus can complete cross-front or along-front surveys on time scales faster than the frontal decorrelation time. The AUVs used in the Pioneer Array are Hydroid REMUS-600 vehicles derived from the original REMUS-100 design (Moline et al., 2005) capable of attaining depths of 600 m. These vehicles have been customised to accommodate the OOI sensor suite. The Pioneer AUVs measure the same 10 variables as the CPMs and track-line gliders, plus nitrate concentration, using 6 different instruments (Table 5). The AUVs have sufficient power to operate the instruments continuously. For standard Pioneer Array missions, the AUVs are operated in a dive-and-climb mode analogous to that of the gliders, creating a saw-tooth sampling pattern in depth (Figure 2) with horizontal resolution about ten times their dive depth. Thus, operating on the shelf, AUVs provide along-track horizontal resolution of order 2 km. The AUVs utilise two 5.4 kWh battery trays providing a nominal endurance of 50 h, after which they require battery recharge. Operationally, a safety margin of about 20% of battery capacity is used, resulting in a nominal mission duration of 40 h covering about 200 km along-track at 1.5 m/s.

The scientific objectives of the AUV operations fall into two main categories: resolving along- and cross-front structure, and investigating cross-front property fluxes. The former objective includes mapping salinity intrusions (both mid-depth and near-bottom), nitrate distributions, and overall frontal structure on time scales shorter than the decorrelation time. The latter objective was originally focused on determining cross-shelf property fluxes using eddy correlation techniques, but due to changes in the AUV concept of operations (see below) is now focused on developing a frontal climatology from which property flux mechanisms can be investigated. These objectives are met using two mission boxes (Figure 7a). Each mission box has long legs of ~47 km and short legs of ~14 km for a total extent of about 120 km. At a typical speed of 1.5 m/s, the mission can be completed in 23 h. A 47 km transect spanning the cross-shelf extent of the moored array (Figure 2) takes about 9 h to complete. The operational approach is to run two vehicles simultaneously, one navigating around each box.

The initial Pioneer Array design included two seafloor docking stations connected to the MFNs of the Inshore and Offshore CSMs. It was estimated that with wind and solar power supplied from the CSM buoy, a docking station could recharge an AUV in 5 days, allowing missions to be repeated once per week. This frequent sampling would provide the necessary statistics to compute seasonal or annual eddy fluxes of heat, salt, and nitrate. However, the docking stations experienced technical difficulties during development and a management decision was made in the summer of 2016 to eliminate the docks from the operational Pioneer Array. The current approach is to operate the AUVs from ships, with missions repeated approximately once per month. This approach will resolve the seasonal evolution of the front and allow generation of a frontal climatology (Linder and Gawarkiewicz, 1998; Fratantoni and Pickart, 2007) which will have better spatial resolution than most prior efforts, consist of both along- and cross-shelf transects, and include several key variables (e.g. dissolved oxygen, chlorophyll and nitrate) not typically available concurrently.

An example of the type of high-resolution sections that the REMUS vehicles provide appears in Figure 2. This section was sampled on May 26, 2016, with the AUV deployed and recovered from a ship during the spring mooring service cruise. The temperature section (Figure 2a) shows a distinct region of relatively cold (<10°C) water over the shelf, with warmer water at depth over the slope and near the surface at the offshore edge of the section. The warm surface water is likely from a warm core ring entrained in the offshore edge of the Shelfbreak Front. This is corroborated by the high salinity in this near surface offshore water (Figure 4b). The Shelfbreak Front is also clearly defined in the salinity field, associated with the 34.5 isohaline. Note that the section resolves the offshore surface outcrop of the front, but does not resolve the foot of the front (bottom outcrop).

### 3.4.4. General Guidelines for the design of shelfbreak observatories

While the Pioneer Array has been designed with the specific shelfbreak processes for the continental shelf and slope south of New England, there are some general principles useful in the design of any shelfbreak observatory.

First, specific information on the space and time scales of dominant shelfbreak processes is absolutely vital. Hydrographic data should be collected at various times in the seasonal stratification cycle to determine the width and annual mean position of jet features, as well as the annual range of stratification. Additional process oriented cruises or preliminary mooring deployments to define spatial and temporal correlation scales would also be of value in the planning stages of a new shelfbreak observatory. The shelfbreak south of New England has been the site of numerous prior experiments, and it is fortunate that correlation scales have been measured as in Table 1. Three particularly important parameters used in setting the mooring locations and spacings in the Pioneer Array were the mean position of the foot of the front, the (cross-shelf) width of the Shelfbreak Jet, and the annual mean cross-shelf position of the core of the Shelfbreak Jet.

Second, when possible, it is advisable to mix both fixed and mobile assets to define detailed time series at fixed locations as well as resolving small-scale features on rapid time scales. Fixed instruments on moorings are extremely useful for resolving internal tides and tidal energy fluxes. Mobile assets, such as AUVs, gliders, or towed vehicles, can resolve features on scales of a few km, which is necessary for resolving sub-mesoscale processes. In combination, fixed and mobile assets provide the capability of both long endurance and high-resolution, both of which are critically important to resolve shelfbreak processes.

Third, many shelfbreak regions around the world are areas of high biological productivity and consequently support intensive commercial fisheries. This necessitates communication and cooperation with stakeholders. Developing reliable mechanisms that reduce multi-use conflicts through negotiations are needed. Discussion forums also provide an opportunity to communicate the importance of the basic science questions and the potential role new observations can play in improving management of both offshore energy systems and commercial fisheries. Obvious examples of observatory science with important practical implications include meteorological and wave measurements from shelfbreak observatories for the offshore energy industry as well as observations of nutrients, chlorophyll fluorescence, and primary productivity to relate to the inter-annual variability of fisheries catches.

Finally, with the increasingly complex challenges posed by climate change in the coastal ocean, it is vital that new perspectives on crucial science results be communicated effectively to resource managers in a timely manner. Examples of critical time-dependent data demands on shelfbreak observatories with important societal implications include hurricanes and winter storms, industrial hazards such as oil spills and nuclear accidents, and search and rescue operations. On longer time frames, using shelfbreak observatory data in offshore energy and fisheries management would be extremely beneficial to all concerned parties. These types of interactions are crucial for the long-term support of ocean science and the motivation of basic science efforts that result in profound new insights into long-standing problems of managing ocean resources.

## 4. Updated science topics

Since the OOI Science Prospectus (2007) and Pioneer Array workshop report (2011) were published, there has been a substantial amount of research on the oceanography and ecosystem dynamics of the continental shelf and slope in the northeast U.S. Many of these studies have identified either changes or processes that can be addressed by the ongoing data collection and analysis from the Pioneer Array. We will briefly discuss two of these topics: Gulf Stream influence and impact on the continental shelf and increasing inter-annual variability of shelf temperatures. The Pioneer Array is well designed to produce data bearing on each of these important scientific topics. In addition, we briefly mention two future challenges, analysis of biogeochemical data and integration of numerical models and remote sensing products into Pioneer Array data analysis.

### 4.1. Gulf stream interactions

The outer continental shelf south of New England is frequently affected by warm core ring interactions. A good example of a case study is Chen, He, et al. (2014), which demonstrates that shelfbreak exchange of heat and salt is increased by an order of magnitude during a week-long interaction with the Shelfbreak Front in 2006. However, in addition to warm core ring interactions, there have been recent events where the north wall of the Gulf Stream moves well north of its normal envelope of motions. In the autumn of 2011, Gawarkiewicz et al. (2012) showed that a surface drifter trajectory with 2 m/s velocities was indicative of the north wall coming very close to the continental shelf along the south flank of Georges Bank. Analysis of the Sea Surface Height Anomaly indicated that it was possible that the 40 cm height contour intersected the shelfbreak during the fall. Anecdotally, commercial lobsterman reported high currents and loss of many lobster traps during the event. Data from the OOI test mooring showed that the extremely high salinities measured during this event over the upper continental slope were only rarely observed in the historical record, occurring less than one per cent of the time in the historical hydrographic observations. This extreme northward diversion of the Gulf Stream was also noted by Ezer et al. (2013) in the Sea Surface Height Anomaly field in September, 2011. They discussed the anomalous Gulf Stream motions in the context of sea level rise.

A possible explanation for the apparent increase in the intensity and frequency of Gulf Stream interactions with the outer continental shelf is the recent westward shift in the destabilisation point, where finite amplitude meandering begins, in the Gulf Stream path. Andres (2016) has shown that the destabilisation point has in recent years moved west of the New England seamount chain. This may be causing the more recent Gulf Stream interactions to be of greater frequency and impact. Another possible factor is the recent discovery that low frequency Gulf Stream motions occur on different time scales east and west of 65° West (Gangopadhyay et al., 2016). To the west, the dominant signals of north–south translation are in the near-decadal band (7-10 years), while motions east of 60°West are predominantly in the 4–5 year range. Secondary peaks of 2–3 years were present throughout the full span of the Gulf Stream path from Cape Hatteras eastward. These low frequency Gulf Stream signals also likely affect the frequency, magnitude, and extent of the Gulf Stream interactions with the Shelfbreak Front and the continental shelf south of New England.

There is an urgent need to examine the Pioneer Array data to determine how Gulf Stream features offshore affect shelfbreak exchange processes and how frequently these interactions occur.

### 4.2. Inter-annual variability and recent warming of the continental shelf

As mentioned previously in Section 2, recent studies such as Mills et al. (2013), Pershing et al. (2015), Forsyth et al. (2015), and Chen, Gawarkiewicz et al. (2014) have highlighted both recent warming trends as well as extreme warming events in the Middle Atlantic Bight and Gulf of Maine. An important scientific challenge is to determine the causes of the warming trends and events, in order to be able to predict future changes as well as mitigate some of the economic impacts, for example on commercial fisheries.

A fundamental scientific question regarding recent warming trends and events is the relative contributions of anomalies in air–sea fluxes versus ocean advective anomalies. Chen et al. (2016) have recently addressed this issue with a numerical model and find that in the time frame 2002–2014 that air–sea flux anomalies were the predominant cause in nine of the twelve years, and ocean advective anomalies were the predominant cause in the other three years.

The Pioneer Array data will be useful in providing more quantitative observations pertaining to the relative breakdown of air–sea flux versus ocean advective contributions to seasonal and inter-annual anomalies. There is a paucity of quality air–sea flux measurements over the outer continental shelf and upper continental slope, and the typical air–sea flux products show a high degree of uncertainty in this geographic region (see Lentz, 2010 for a thorough discussion of this issue). Similarly, the gliders provide information in shifting temperatures of inflowing waters from the Gulf of Maine and Georges Bank into the Middle Atlantic Bight, as well as onshore flows from slope and Gulf Stream waters. Comparing the Pioneer Array data with numerical models is important in order to build confidence in our understanding of the causes of inter-annual variability.

### 4.3. Future challenges

To date, the full potential of the Pioneer Array multidisciplinary data set has not been fully realised. This is particularly true for bio-geochemical processes. While low oxygen events and associated crab mortality have been examined for the Endurance Array on the west coast of the United States (Barth et al., 2018) and biological carbon cycling processes in both the surface layer and thermocline have been examined in the Irminger Sea (Palevsky and Nicholson, 2018), the biogeochemical data from the Pioneer Array have yet to be analysed and reported in the scientific literature. A crucial science issue, as mentioned in the report from the Science Themes workshop, is the issue of cross-shelf transport of nutrients from the continental slope to the continental shelf. This is particularly important now, as evidence for offshore forcing impacting the continental shelf in recent years has been extensive (Gawarkiewicz et al., 2018). It is highly likely that this has major ramifications for both annual nutrient budgets for the continental shelf and large inter-annual variations in the amount of nitrate carried onto the shelf from the deep ocean. We note that the bio-geochemical data is publicly available on the Ocean Observatories Initiative website, which includes data collected from the moorings, from mobile assets, and from the mooring turn-around cruises.

A further challenge is the use of Pioneer Array data in computational simulations of both shelfbreak exchange processes and ecosystem dynamics. Efforts are currently underway in a number of academic institutions to use data from this observatory to model circulation and nutrient dynamics. A general issue that both the observations and computational simulations must address is how representative remote sensing of sea surface temperature, ocean colour, and sea surface height anomalies are for sub-surface exchange processes. Establishing these relations between remote sensing processes and sub-surface observations is important in creating a long-term legacy of scientific understanding for the Pioneer Array.

To date, the Pioneer Array has enabled the discovery of new shelfbreak exchange processes, has shown that offshore forcing is increasingly important to the continental shelf, and has successfully combined high-resolution observations with long endurance over multiple years. Given the economic importance of the New England shelfbreak to the commercial and recreational fishing industries and the impacts of warming the continental shelf on future storm intensities, it is clear that future research involving the Pioneer Array will have important economic and societal impacts.

## 5. Summary and conclusions

The OOI Pioneer Array is a unique process-oriented multi-scale shelfbreak observatory that is currently in operation. The observatory has three main observing components: moorings, gliders, and AUVs. All three are necessary to provide both long duration (five years) and high resolution (down to metres) required to resolve shelfbreak exchange processes.

The recent scientific literature relating to both warming of the continental shelf in the region as well as further studies of shelfbreak exchange are briefly highlighted and discussed. This updates the relevant research from the science workshop for the Pioneer Array that was released in 2011. The basic design principles of the observatory are described, along with a summary of how the design is implemented for the Pioneer Array.

One of the byproducts of the Ocean Observatories Initiative is interest in development of new ocean observatories around the world. For example, China is developing ocean observatories with cables spanning the continental shelf in both the East China Sea and the South China Sea. In the Bay of Bengal, the Indian Institute of Technology-Bhubaneshwar and the National Institute of Ocean Technology in Chennai are working jointly to build an observatory spanning the continental shelf and slope. We hope that future shelfbreak observatories can learn from the scientific rationale and design principles for the OOI Pioneer Array described here.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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## Appendix 1. Role of the Commercial Fisheries Research Foundation

The Commercial Fisheries Research Foundation (CFRF) ran the meetings between commercial fishing representatives and scientists representing the Pioneer Array and produced a report at the end with recommendations to reduce potential conflicts that was agreeable to both parties. The moderator role was ably performed by Margaret Petruny-Parker, Executive Director of the Foundation. One of the participants, Anna-Marie Laura, was a staff member of Senator Whitehouse of Rhode Island. At the end of the negotiations, she complimented the skillful guidance of Ms. Petruny-Parker, the spirit of cooperation between the fishing industry representatives and the science representatives, and stated that these negotiations could serve as a model for future multi-use conflict resolution in the waters of southern New England.

The CFRF report, entitled Pioneer Array Workshops – Exploration of Issues and Concerns Connected with the Planned OOI Pioneer Array Project, is available at http://www.cfrfoundation.org/pioneer-array-workshop-series.