Collaborative Research:
Shelfbreak frontal dynamics: mechanisms of upwelling, net community production, and ecological implications

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Project Summary

The continental shelfbreak of the Middle Atlantic Bight supports a productive and diverse ecosystem. Current paradigms suggest that this productivity is driven by several upwelling mechanisms at the shelfbreak front. This upwelling supplies nutrients that stimulate primary production by phytoplankton, which in turn leads to enhanced production at higher trophic levels. Although local enhancement of phytoplankton biomass has been observed in some synoptic measurements, such a feature is curiously absent from time-averaged measurements, both remotely sensed and *in situ*. Why would there not be a mean enhancement in phytoplankton biomass as a result of the upwelling? One hypothesis is that grazing by zooplankton prevents accumulation of biomass on seasonal and longer time scales, transferring the excess production to higher trophic levels and thereby contributing to the overall productivity of the ecosystem. However, another possibility is that the net impact of these highly intermittent processes is not adequately represented in long-term means of the observations, because of the relatively low resolution of the *in situ* data and the fact that the frontal enhancement can take place below the depth observable by satellite.

A unique opportunity to test these hypotheses has arisen with deployment of the Ocean Observatories Initiative (OOI) Pioneer Array south of New England. The combination of moored instrumentation and mobile assets (gliders, AUVs) will facilitate observations of the frontal system with unprecedented spatial and temporal resolution. This will provide an ideal four-dimensional (space-time) context in which to conduct a detailed study of frontal dynamics and plankton communities needed to test the aforementioned hypotheses.

We propose a set of three cruises to obtain cross-shelf sections of physical, chemical, and biological properties within the Pioneer Array. Nutrient distributions will be assayed together with hydrography to detect the signature of frontal upwelling and associated nutrient supply. We expect that enhanced nutrient supply will lead to changes in the phytoplankton assemblage, which will be quantified with conventional flow cytometry, imaging flow cytometry (Imaging FlowCytobot, IFCB), *in situ* optical imaging (Video Plankton Recorder, VPR), traditional microscopic methods, and HPLC pigments. Zooplankton will be measured in size classes ranging from micro- to mesozooplankton with the IFCB and VPR, respectively, and also with microscopic analysis. Biological responses to upwelling will be assessed by measuring rates of primary productivity, zooplankton grazing, and net community production. These observations will be synthesized in the context of a coupled physical-biological model to test the two hypotheses that can potentially explain prior observations: (1) grazer-mediated control and (2) undersampling. Hindcast simulations will also be used to diagnose the relative importance of the various mechanisms of upwelling.

The **intellectual merit** of this effort stems from our interdisciplinary approach, advanced observational techniques, and integrated analysis in the context of a state-of-the-art coupled model. The proposed research will address longstanding questions regarding hydrodynamics and productivity of an important ecosystem, leading to improved understanding of physical-biological interactions in a complex continental shelf regime. Given the importance of frontal systems in the global coastal ocean, we expect that knowledge gained will have broad applicability beyond the specific region being studied here.

Broader impacts include (1) promoting teaching, training and learning via participation of graduate and undergraduate students in the proposed research , (2) broad dissemination by means of outreach in public fora, printed media, and a video documentary of the field work, and (3) improving societal well-being and increased economic competitiveness by providing the knowledge needed for science-based stewardship of coastal ecosystems, with particular emphasis on connecting with the fishing industry through the Commercial Fisheries Research Foundation.

This collaborative proposal involved partners from WHOI ($1,993,156), UMass Dartmouth ($461,615), VIMS ($420,394), and Wellesley ($103,583) for a total of $2,978,748.

Preamble: This revision of a prior proposal addresses reviewer concerns by (1) strengthening the rationale for the project, introducing a new hypothesis to explain the lack of enhancement of seasonal mean chlorophyll at the shelfbreak front, (2) addition of triple oxygen isotope and oxygen/argon measurements, providing additional constraints on gross primary production and net community production, as well as expanding the space and time scales to which our suite of observations apply, (3) augmenting our plans for extrapolating discrete rate measurements to larger space and time scales, and (4) clarifying our sampling strategy. Lastly, we have attempted to emphasize the novelty of the proposed research by highlighting the unique opportunity to use advanced observational infrastructure to assess quantitatively the relative importance of bottom-up and top-down controls on plankton populations in a highly dynamic frontal system—and that understanding gained from this study will be applicable to many other regions of the global coastal ocean where frontal phenomena are pervasive.

1. Introduction

The Middle Atlantic Bight (MAB) shelfbreak is a region of high biological productivity (Marra et al. 1990, O'Reilly et al. 1987, Ryan et al. 1999b). Large horizontal and vertical gradients in water properties and persistent upwelling are associated with the shelfbreak front, a feature susceptible to nonlinear instabilities and strong interactions with Gulf Stream warm-core rings that impinge on the continental slope (Barth et al. 2004, Houghton et al. 1994, Linder et al. 2004, Lozier et al. 2002, Ryan et al. 2001). Long-term studies suggest both persistence of the shelfbreak jet, as well as upstream advective influences from the Scotian shelf (Bisagni et al. 2006, Flagg et al. 2006). As a result, this region has significant along- and cross-shelf fluxes of heat, freshwater, nutrients, and carbon that control the water mass characteristics and the ecosystem, both at the shelfbreak and in the neighboring shelf and slope (Falkowski et al. 1988, Greer et al. 2015, Houghton & Marra 1983, Malone et al. 1983, Marra et al. 1982, Ryan et al. 1999a,b, Vaillancourt et al. 2005, Walsh et al. 1988). Both satellite and *in situ* observations reveal synoptic enhancement of phytoplankton biomass at the front, although such enhancements are not always present (Hales et al. 2009).

Despite numerous studies, both observational (Biscaye et al. 1994, Flagg et al. 2006, Houghton et al. 2009) and numerical (Chapman & Lentz 1994, Chen & He 2010, Gawarkiewicz & Chapman 1992), our understanding of the processes that control the circulation and ecosystem dynamics of the shelfbreak front is still inadequate. The primary reason is that shelfbreak frontal processes are inherently nonlinear and exhibit variations over a broad range of spatial and temporal scales. To grapple with this complexity, Linder and Gawarkiewicz (1998) combined historical temperature and salinity observations and generated a seasonal two-dimensional (2D) cross-shelfbreak climatology for subregions of the MAB. Similarly, Fleming and Wilkin (2010) generated a monthly 3D climatology of temperature and salinity for the entire MAB. These climatologies provide a description of the mean state that serves as a baseline for studying temporal and spatial variability of the frontal dynamics.

Associated with the shelfbreak front are strong vertical motions, which may significantly influence the shelfbreak ecosystem. Specifically, upward

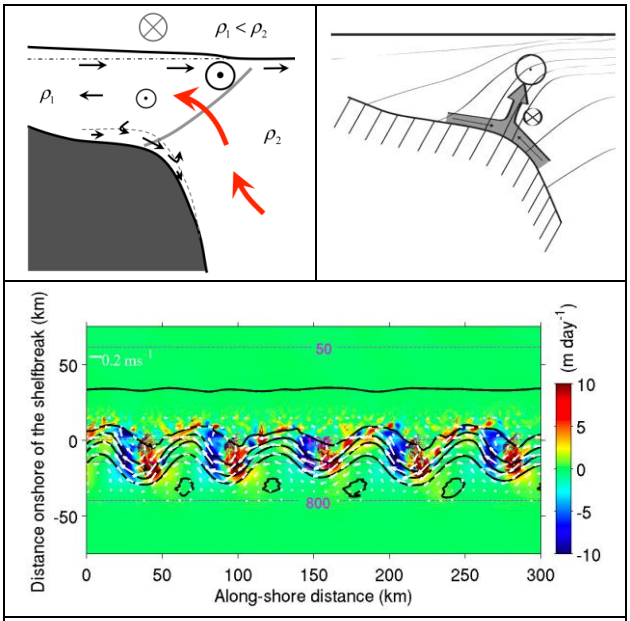

Fig. 1. Three upwelling mechanisms at the shelfbreak. Upper left: mean upward motion (red arrows) driven by divergence in the onshore interior flow (Zhang et al. 2011). Upper right: along-isopycnal upwelling associated with convergence in the bottom boundary layer (Linder et al. 2004). Bottom: vertical motion associated with frontal meandering in an idealized simulation (Zhang & Gawarkiewicz 2015b). Colors, white arrows, and black lines indicate vertical velocity, horizontal velocity, and isopycnal contours (interval of 0.1 kg m^{-3}) at 40 m; magenta lines are isobaths.

motion could deliver nutrients into the euphotic zone and stimulate local primary productivity during periods when nutrients are depleted. There are multiple mechanisms of shelfbreak upwelling (Fig. 1). Although the processes regulating this vertical motion are complex, simple models can be useful for understanding key aspects, such as frontogenesis (Benthuysen & Thomas 2013) and buoyancy shutdown (Benthuysen et al. 2015). Based on the fact that density is approximately uniform in the along-shelf direction (Lentz 2010), Zhang et al. (2011) employed a 2D (cross-shelf and vertical) model and the 3D temperature and salinity climatology (Fleming & Wilkin 2010) to examine the annual and seasonal mean circulation around the New England shelfbreak. Analysis of the solutions facilitated distillation of a simple schematic of the mean flows and secondary circulation at the front (Fig. 1, upper left). To summarize, sloping isopycnals cause a geostrophically balanced alongshore flow in the interior that is augmented by a cross-shelf tilt in sea level. Flows are directed offshore in the surface and bottom boundary layers, because of an eastward along-shelf component of the mean wind stress in the former and bottom Ekman layer dynamics in the latter. An along-shelf pressure gradient drives onshore flow in the interior, leading to upwelling at the shelfbreak as a result of continuity. The associated mean vertical velocity varies seasonally from tens of cm d^{-1} in summer to a few m d^{-1} in winter (Zhang et al. 2011).

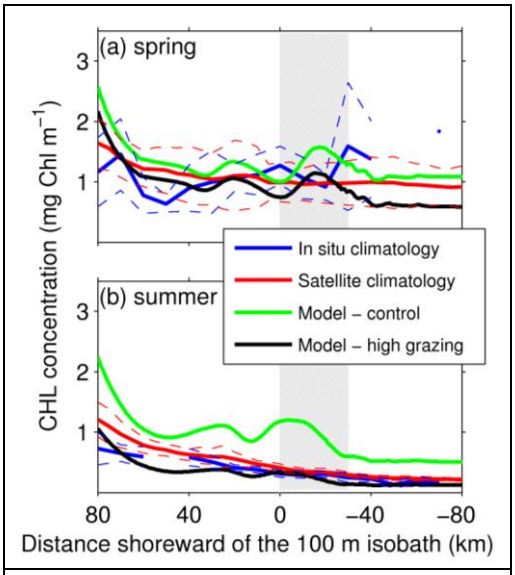

Fig. 2. Observed and simulated cross-shelf distributions of chlorophyll (Zhang et al. 2013). Dashed lines are the 95% confidence intervals for the means. Gray shading indicates the envelope of the front.

This mechanism differs from the upwelling associated with the convergence in the bottom boundary layer (Fig. 1, upper right; Chapman & Lentz 1994, Linder et al. 2004, Pickart 2000). Observations at the shelfbreak (Barth et al. 1998, Houghton & Visbeck 1998) have shown convergence of the cross-shelf bottom flows near the foot of the shelfbreak front, leading to abrupt detachment of the bottom boundary layer and then upwelling into the interior with vertical velocity up to 9 m d^{-1}. Yet another mechanism of upwelling derives from instability-driven meandering of the shelfbreak front (Fig. 1, bottom; Zhang & Gawarkiewicz 2015b). As demonstrated by studies in the open ocean (Lévy et al. 2001, Mahadevan & Archer 2000, Woods 1988), frontal instability can induce strong vertical motion (several to tens of m d^{-1}) through mesoscale and submesoscale vorticity dynamics. Lastly, we note that surface Ekman transport divergence can cause upwelling at the shelfbreak front (Csanady 1984), although the associated vertical velocity is only 10^{-5} m d^{-1} for typical conditions at the New England shelfbreak (Zhang et al. 2011).

All of these upwelling mechanisms would deliver nutrients to the euphotic zone, thereby increasing productivity. However, because the associated spatial and temporal scales are dramatically different, the overall strength of these different types of upwelling and the relative importance of the vertical nutrient fluxes associated with each are not well constrained. Curiously, there does not appear to be a significant enhancement in the seasonal mean cross-shelf distribution of chlorophyll in either satellite-based or *in situ* data sets (Fig. 2), despite the variety of upwelling processes thought to be active at the front. **Why would there *not* be an enhancement of mean chlorophyll associated with the mean upwelling?** Zhang et al. (2013) investigated this in a simple nutrient-phytoplankton-zooplankton-detritus model coupled to the aforementioned 2D circulation model. Whereas a control run exhibits chlorophyll enhancement at the front during the spring and summer as a result of upwelling, enhanced top-down control by zooplankton in a "high grazing" case can prevent accumulation of phytoplankton biomass (Fig. 2, Cf. green and black lines). We regard this latter model solution as a hypothesis in need of testing in the field. Alternatively, physical transport could also play a role in diminishing enhancement of phytoplankton biomass at the front. However, physical processes such as advection or diffusion are not likely to be the primary cause of the absent frontal biomass enhancement, as the same processes would also suppress the frontal density

gradient. In any case, our models (section 4) will include explicit representation of those effects. To summarize, our hypotheses are:

H_1: Upwelling at the shelfbreak front results from a combination of (1) onshore interior flow driven by an along-shelf pressure gradient, (2) convergence in the bottom boundary layer, (3) vortex stretching driven by frontal meandering and associated mesoscale/submesoscale dynamics, and (4) Ekman divergence in the surface boundary layer.

H_2: These upwelling processes result in local enhancement of nutrient fluxes into the euphotic zone.

H_3: Enhanced nutrient availability stimulates increased primary productivity in the front and leads to changes in the phytoplankton species assemblage.

H_{4a}: Autotrophic biomass does not accumulate in areas of frontal upwelling because of zooplankton grazing; this grazer-mediated control is reflected in both zooplankton biomass and species composition.

H_{4b}: Autotrophic biomass does accumulate in areas of frontal upwelling, but the spatial and temporal intermittency of these events causes their net impact to be smoothed out in long-term means of historical observations of nutrients and chlorophyll.

The hypothesis of top-down control (H_{4a}) has been examined in detail in other regions such as the subarctic Pacific (Banse 1990, Frost 1993), with recent foci by the GLOBEC program in the northeast Pacific (Batchelder et al. 2005) and BEST programs (Lomas & Stabeno 2014), the latter of which highlighted trophic dynamics of the "green belt" (Springer et al. 1996) at the Bering Sea shelf edge. We note this is a particularly challenging hypothesis to test at the MAB shelfbreak front, owing to the highly dynamic nature of the frontal system and the small spatial scales (km) and short temporal scales (days) of the attendant processes. A competing hypothesis to explain the lack of enhancement of the mean chlorophyll at the front is undersampling in prior *in situ* observations (H_{4b}). As for undersampling by remote sensing, this could potentially be explained by the fact that frontal chlorophyll enhancement takes place subsurface (Marra et al. 1990), too deep to be detected in satellite ocean color.

We will adopt a coupled observational and modeling strategy to test our set of five linked hypotheses. We propose a set of three cruises to be carried out in the vicinity of the Ocean Observatories Initiative (OOI) Pioneer Array. Real-time data streams from the Pioneer Array as well as satellite remote sensing will be used to guide adaptive sampling of physical, biological, and chemical properties. The resultant data sets will yield direct observational tests of H_2, H_3, and some aspects of H_{4a}. Testing of H_1 and the unobserved aspects of H_{4a} will be carried out with a data assimilative coupled physical-biological model. Evaluation of H_{4b} will be facilitated by long-term averages of the Pioneer data, as well as model-based assessment. We expect what is learned to be broadly applicable to other frontal regimes, for which there are many throughout the global coastal ocean (Robinson & Brink 1998).

2. Context for the proposed research: the OOI Pioneer Array

The wide range of space and time scales relevant to the processes of interest necessitates a multi-scale approach, and the OOI Pioneer Array provides the required infrastructure. Key data streams for this research come from gliders (Rudnick et al. 2004, Sherman et al. 2001) and the moored array. A set of glider tracks (Fig. 3) obtained from the OOI data portal (OOI 2016) illustrates how these data would be used in our study.

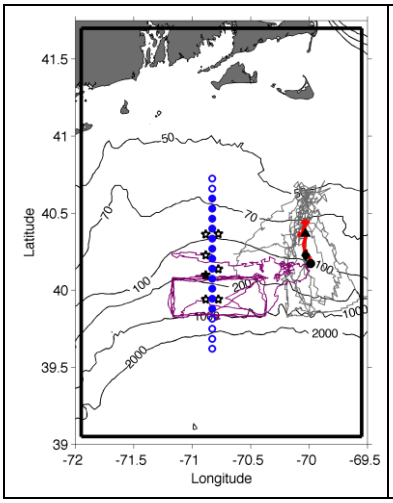

Fig. 3. Tracks of Pioneer Array gliders (grey, magenta lines), 17 Apr – 30 Jun 2014. Red line is a cross-shelf transect on 25-26 Apr (Fig. 4); the black triangle, diamond, and circle indicate the positions of the foot, jet and surface expression of the front, respectively. Mooring locations are shown as stars, with the central offshore mooring (Fig. 5) filled in black. Proposed shipboard transects indicated with blue circles. The solid black boundary depicts the NESEC model domain (section 4).

Along-track temperature and salinity distributions (Fig. 4) will be used to identify the foot of the front (where the pycnocline intersects the bottom), the location of the shelfbreak jet (where the density gradient at 40 m is maximal), and the near-surface expression of the front. Similar diagnostics can be derived from the moored array (stars in Fig. 3). Time series of temperature, salinity, and chlorophyll from the central offshore mooring (Fig. 5) highlight the energetic high-frequency variability characteristic of the region. Nevertheless, clear low-frequency trends of particular interest are visible: shoaling of the front from April 17 to April 23, followed by meandering of the front with a period of 3-4 days (dashed lines in Fig. 5).

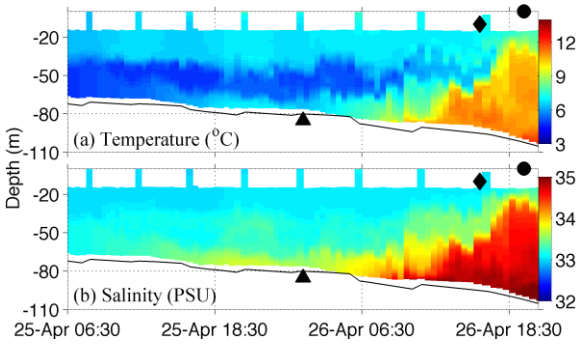

Fig. 4. Temperature and salinity from a glider as it transited in the offshore direction (Fig. 3, red track). Shoaling of isothermal and isohaline surfaces on 26 April is associated with the shelfbreak front. Approximate positions of the foot, jet, and surface expression of the front are indicated by the triangle, diamond and circle, respectively. The subsurface temperature minimum onshore of the front is likely part of the cold pool (Houghton et al. 1982).

Data from the gliders and moorings will be used in two ways. First, real-time data streams will be used to estimate the location of the front and orient our shipboard transects (section 3). For example, the glider and mooring data from April 2014 (Figs. 4,5) suggest the front is well shoreward of its mean position, likely due to the influence of an adjacent warm-core ring (not shown). Therefore, the twelve-station ship transect we propose (section 3) is near the northernmost extent of the expected envelope (Fig. 3). The second use of the glider and mooring data will be for numerical modeling (section 4). In short, the physical oceanographic data will be assimilated into hydrodynamic hindcasts, whereas the biological data will be used to evaluate the coupled plankton model.

Within the Pioneer Array, a combination of discrete-depth and profiling sensors will provide temperature, conductivity, and velocity throughout the water column. Additional instrumentation will include oxygen, nutrient, and bio-optical sensors (fluorometers, radiometers, and backscattering, attenuation and absorption meters). The optical sensors will be important for providing indices of concentration and characteristics of phytoplankton (e.g., chlorophyll, particulate carbon concentration) and particle size distribution (Sosik 2008). The combination of moored and profiling nutrient and irradiance sensors, plus local surface forcing and extensive subsurface hydrographic data, will provide unprecedented detail on the various impacts of physical forcing on light and nutrient availability that affect the growth and distribution of different types of phytoplankton.

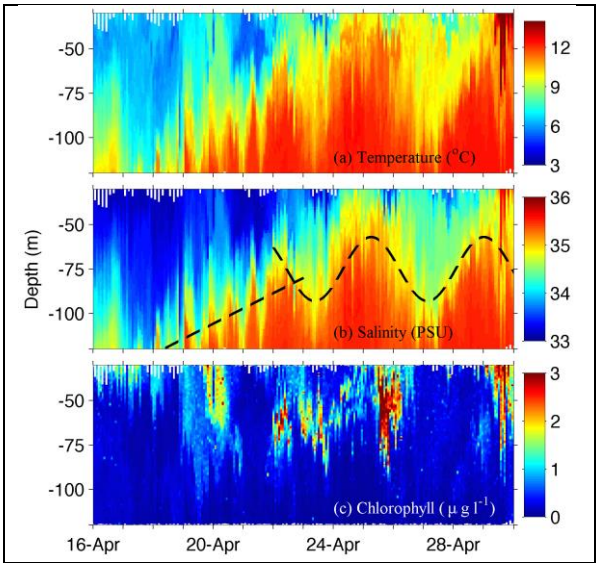

Fig. 5. Temperature, salinity, and chlorophyll at the central-offshore mooring (Fig. 3). Dashed lines in (b) indicate 1) gradual shoaling of isopycnals during 17-22 April caused by onshore migration of the front, and 2) vertical oscillation of isopycnals with a period of 3-4 days over 23-30 Apr caused by frontal meanders. Higher frequency changes are likely internal waves or inertial oscillations.

We note that selected surface buoys house meteorological sensors for air temperature, specific humidity, sea surface temperature and conductivity, wind speed and direction, barometric pressure, short- and longwave radiation, and precipitation. These measurements will be used to compute air-sea fluxes of heat, moisture and momentum with bulk aerodynamic formulas to provide realistic forcing estimates for evaluating adjustments to the surface forcing by the data assimilation procedure (section

4.1). These computations will also be of value in constraining air-sea gas fluxes (section 3.6).

3. Seagoing process studies

We propose three cruises of 14 days each: spring 2018, summer 2018, and spring 2019. The two cruises in year one will provide contrast between the springtime period when ephemeral enhancement of phytoplankton biomass is most visible from satellite data (Ryan et al. 1999a) and more stratified conditions when the response may be muted (Hales et al. 2009), especially in the near-surface region. The final cruise in spring 2019 will provide additional sampling at a time when we expect the signal to be maximal; comparisons with spring 2018 will permit an assessment of between-year variability. This latter aspect is particularly important in light of the potential for warm-core Gulf Stream rings to perturb the system (Chen et al. 2014, Flierl & Wroblewski 1985, Joyce et al. 1992, Zhang & Gawarkiewicz 2015a).

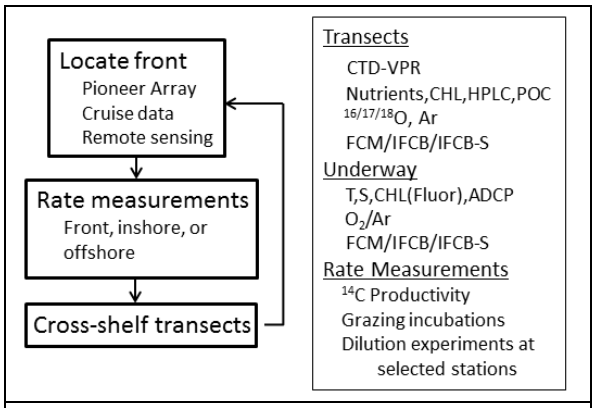

Fig. 6. Daily sampling cycle (left) and summary of measurements (right).

Our observational plan consists of cross-frontal transects and rate measurements, conducted in a daily cycle of activity (Fig. 6). Each day will begin with determining the precise location of the front from a combination of data from the Pioneer Array, cruise observations, and remote sensing images. Rate measurements will start at dawn each day, strategically located in one of the three key regimes: inshore, offshore, and at the front. Twelve repetitions of the observational cycle (see below) will permit four replicates in each of the three regimes, facilitating estimates of the mean and variance for each.

Fourteen-day cruises will allow for 12 science days, assuming one-day transits to and from the sampling area. Our plan is to conduct 12 cross-frontal transects, each taking ca. 24 h (Fig. 3). Each transect will be composed of 12 stations spaced 7 km apart. Our rationale for 12 sections stems from the fact that meandering of the shelfbreak front is a major source of variability of the hydrographic and biological states. Based on repeated surveys, Gawarkiewicz et al. (2004) reported that 1) spatial decorrelation scales for temperature, salinity, and velocity in the upper 60 m were 8-15 km, with temporal decorrelation scales of ~1 day; 2) frontal variability was dominated by passage of a westward propagating meander with wavelength of 40 km and period of 4 days (propagation speed ~0.11 m s^{-1}). Analysis of recent subsurface measurements in the same region gave similar horizontal scales of frontal variability (Todd et al. 2013, Zhang & Gawarkiewicz 2015b). Each of our 24-hour cross-shelf transects will provide one statistically independent snapshot of the cross-shelf distribution of physical and biological properties, and the 12 transects in each cruise will cover ~3 cycles of the dominant frontal meander scale.

To achieve our goals for the cross-shelf transects, we must combine physical measurements with concurrent biological observations. We will make detailed surveys that provide biomass, rates of net community and gross primary production, and high resolution observations of taxonomic composition and size structure of the plankton. We will use state-of-the-art observational approaches that allow these biological characteristics to be observed rapidly enough for the proposed cross-shelf station transects. The surveys will be complemented by strategically-located rate measurements of primary production and zooplankton grazing. Because these multiple approaches will provide information across multiple trophic levels, we will be able to investigate physical forcing, bottom-up processes, and grazer-mediated controls as they interact to influence plankton community structure and associated food web dynamics.

3.1 Physical oceanographic measurements

High-resolution transects are essential for understanding the spatial and temporal structure of cross-shelf gradients within the shelfbreak front. A shipboard ADCP will provide continuous measurements of horizontal velocity throughout the water column. We will also measure vertical profiles of temperature and salinity at all cross-shelf CTD stations concurrent with biological sampling. These observations will provide high-resolution quasi-synoptic views of the cross-shelf distribution of frontal gradients, including the position and strength of the shelfbreak front and jet. These will be used to identify key dynamical

parameters of the front (e.g., cross-shelf convergence/divergence, upwelling/downwelling, bottom boundary layer detachment, surface and subsurface onshore intrusions) at the times and locations of the biological measurements. These measurements are essential for understanding physical-biological interactions at the shelfbreak front, and will provide crucial subsurface constraints for the data assimilative model in hindcasting our cruise periods (see section 4).

3.2 Nutrients

Samples will be drawn from Niskin bottles at 12 discrete depths. To reduce the analysis load, we will sample either every other station or every other transect, such that the number of samples generated per cruise is 864 (12 transects · 12 stations · 12 depths / 2). Samples will be syringe-filtered and frozen, and later processed at the WHOI Nutrient Analytical Facility with standard AutoAnalyzer techniques.

3.3 Flow cytometry for phytoplankton and microzooplankton

Conventional flow cytometry – Pico- and small nano-phytoplankton will be enumerated and sized with conventional laser-based flow cytometric (FCM) analysis using a BD Accuri C6 flow cytometer (BD Biosciences). We will conduct analyses on discrete samples collected from depth profiles, as well as on a continuous stream from the ship's seawater intake to provide higher resolution for surface waters along-track. At least 200 μL samples will be analyzed. Due to small sample volumes and dynamic range limits, these FCM measurements will be practical for analysis of ~1-20 μm cells. The measurements will include individual cell-based assessments of chlorophyll and phycoerythrin fluorescence, permitting picocyanobacteria and cryptophytes to be unambiguously distinguished from a mixture of other pico- and nano-sized eukaryotic phytoplankton (e.g., Olson et al. 1993, Sosik et al. 2010). Individual cell light scattering will be converted into cell volume estimates on the basis of calibration with independently sized cell cultures following approaches we have previously developed (DuRand et al. 2002, Laney & Sosik 2014, Olson et al. 2003). When integrated with measurements of larger phytoplankton (described next), this approach will allow us to assess quantitatively how phytoplankton size spectra change across the shelfbreak front.

Imaging FlowCytobot – Imaging-in-flow cytometry will be used to extend the FCM-based observations into the microplankton range, including chain-forming species. IFCB measures not only fluorescence and light scattering, but also captures a high resolution (~1 μm) image of each cell or chain (Fig. 7); it is also optimized to analyze larger sample volumes (5 mL) to improve sampling statistics for rare microplankton (Olson & Sosik 2007). This standard IFCB (and Staining IFCB described below) will be used for analysis of discrete samples from vertical profiles, underway surface sampling, and grazing experiments (section 3.8). We have previously shown that IFCB provides sampling of many phytoplankton taxa with performance that is equivalent to or better than results from conventional manual microscopy (Brosnahan et al. 2015, Campbell et al. 2010, Olson & Sosik 2007). IFCB produces large numbers of images (typically 10^5 h^{-1} in coastal waters), so manual analysis will be prohibitive. We will automatically analyze images and assign them to taxonomic groups following approaches we have developed for the multi-year IFCB time series at the Martha's Vineyard Coastal Observatory (Peacock et al. 2014, Sosik & Olson 2007). For taxonomic identification, we will manually inspect and identify images to produce training sets to develop automated classifiers (genus or species level) following the approach in Sosik and Olson (2007), except with a Random Forest classifier algorithm (Breiman 2001) in place of the support vector machine. Estimation of particle size from light scattering is highly uncertain for these large, inhomogeneous, irregularly shaped particles, so we will use image analysis to estimate dimensions and individual cell biovolumes (Moberg & Sosik 2012, Sosik & Olson 2007). We will use this information to compute abundance and biomass-based size spectra for various taxonomic groupings (e.g., from single species to aggregation of all diatoms). To facilitate this work, we will

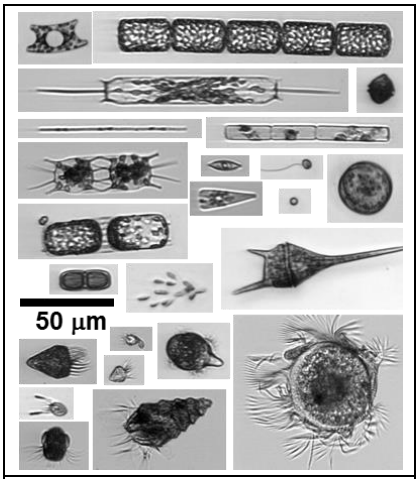

Fig. 7. Example plankton images collected by IFCB during deployments at the Martha's Vineyard Coastal Observatory.

take advantage of an informatics pipeline we developed to handle these large data sets, enabling image analysis, feature extraction, classification, error correction, and open access to image data and results (Sosik & Futrelle 2012).

Staining Imaging FlowCytobot – The standard IFCB is optimized for sampling of phytoplankton (through triggered imaging of particles that exhibit chlorophyll fluorescence), but it also has proven very effective for imaging and identification of many types of protozoa, notably those that are either mixotrophic or contain fluorescent prey in their guts (Fig. 7 right, rows below the scale bar). The Staining IFCB (IFCB-S), recently developed in the Sosik lab, will allow us to quantify protozoa more completely because it has added features that enable automated incubation of samples with a live cell fluorescent stain (Brownlee et al. 2016). We will operate the IFCB-S continuously during underway surface sampling, and as time permits, for analysis of discrete samples from CTD casts and incubation experiments. The same data analysis and processing pipeline developed for phytoplankton images will be applied to these data (which will include phytoplankton, along with the protozoa).

3.4 Pigment and POC analysis

Particulate material from discrete water samples (1-2 L from CTD casts and selected underway samples) will be collected onto GFF filters under <5 mm Hg vacuum pressure, and then immediately stored in liquid nitrogen to preserve phytoplankton pigments. Chlorophylls and accessory pigment concentrations will be determined by standard high performance liquid chromatography (HPLC) methods (Hooker et al. 2005, Van Heukelem & Thomas 2001). We expect to collect ~240 HPLC samples (including ~5% replicates) from each cruise. Post-analysis processing will include customized application of CHEMTAX (Mackey et al. 1996), an optimization procedure for chemotaxonomic characterization of different phytoplankton classes (e.g., diatoms, dinoflagellates, prymnesiophytes, cyanobacteria, cryptophytes, etc.) on the basis of marker pigment and diagnostic pigment ratios. If merited by residual analysis, separate optimization runs will be conducted for different depth layers or cross-shelf zones. These analyses will complement the flow cytometry and imaging flow cytometry by providing information about taxa that are difficult to distinguish by optical cross-sections or light microscopy (e.g., pico- to small nano-sized prymnesiophytes and prasinophytes). Size-fractionated (whole water and <20 μm) chlorophyll samples filtered onto GFF filters will be frozen for later fluorometric analysis, whereas appropriate volumes (0.5-2 L) for POC will be filtered through combusted GFF filters, placed in combusted glass vials, covered with aluminum foil, and dried at 60˚C (Gardner et al. 2000). Samples will be analyzed on a Costech ECAS 4010 elemental analyzer at VIMS. Blanks are filters through which ca. 5 mL filtered seawater has been passed. As with HPLC, replicates will be processed for ~5% of all samples.

3.5 Net primary productivity

Size-fractionated primary productivity will be measured with simulated *in situ* techniques (e.g., Harrison et al. 1985, Lohrenz et al. 1991, Smith et al. 2000). Samples will be collected from known isolumes and placed in sterile 285 mL Qorpak bottles, to which ~20 μCi $NaH^{14}CO_3$ will be added. Bottles will be placed in an on-deck incubator through which surface seawater flows to maintain appropriate temperatures; irradiance will be attenuated by neutral density filters to mimic those at the depths sampled (with blue filters at isolumes below 30% E_o; (Laws et al. 1990)). Irradiance will be quantified using a BioSpherical Instruments sensor placed near the incubators. After 24 h, samples will be filtered through GFF filters and placed in 7 mL scintillation vials. Size fractionations will be completed at all stations using 20 μm Poretics filters on subsamples from each bottle. 100 μL 1N HCl will be added to volatilize absorbed inorganic ^{14}C. Ecolume (5 mL) will be added to each vial, and all vials will be counted after 24 h on a liquid scintillation counter at sea. Total activity will be measured by counting 100 μL of non-acidified sample in β-phenethanylamine (Smith et al. 2000).

While the ^{14}C method is relatively "standard", interpretation of the results is not. Specifically, the start of incubations can bias each measurement due to the relative importance of nocturnal phytoplankton respiration (e.g., Marra 2009, McAllister et al. 1964). To help us compare results, we will sample three locations at the same time each day: shelf, shelfbreak, and slope. We will also conduct time-course measurements to try to assess the relative importance of respiration at each location to facilitate spatial comparisons. Most importantly, all grazing experiments (section 3.8) will be conducted at the same

stations as primary productivity measurements to allow a direct assessment of growth and loss processes in controlling phytoplankton biomass.

3.6. Net community productivity and gross primary productivity

In situ gas tracers will be used to quantify net community productivity (NCP) and gross primary productivity (GPP) at all stations, providing rate estimates that average over temporal scales of 2-3 days. Spatial variability on order of kilometers has frequently been observed in rates calculated from these tracers (Estapa et al. 2015, Lockwood et al. 2012, Stanley et al. 2010) and thus the data will be able to reflect any changes in rates of productivity across the shelfbreak. The large number of rates calculated by this method will complement the incubation-based biological productivity and grazing measurements that are less numerous. Measurement of GPP will be especially useful for testing H_3. If the enhanced shelfbreak productivity is due to grazer-mediated control, then rates of GPP at the shelfbreak front should be large, compared to surrounding waters, as the phytoplankton must have first photosynthesized before they were consumed. If there is no enhancement due to bottom-up control, then rates of gross O_2 productivity at the shelfbreak front will be similar to surrounding water. NCP rates will enable us to calculate a ratio of NCP:GPP which is a measure of the export efficiency and which, according H_{4a}, will peak at the shelfbreak.

GPP will be determined by measurements of the triple O_2 isotope ratio of dissolved oxygen since photosynthetic processes result in mass dependent fractionation, whereas stratospheric processes lead to mass independent fractionation of O_2 mixed into the water during gas exchange (Juranek & Quay 2013, Luz & Barkan 2000). Thus the triple O_2 isotope ratio quantifies the fraction of dissolved O_2 arising from photosynthesis. Samples (300 per cruise) will be collected from the surface at every station to obtain detailed spatial resolution and at 4 additional depths for ¼ of the stations to make corrections for vertical transport. The samples will be collected in custom-made, pre-poisoned evacuated flasks (Emerson et al. 1991) and measured on the isotope ratio mass spectrometer at WHOI (Stanley & Howard 2013, Stanley et al. 2015). Sample precision on that system is typically better than 5 per meg for $^{17}\Delta$, 0.01 per mil for $\delta^{17}O$, and 0.008 for $\delta^{18}O$. Rigorous quality control is performed through daily analysis of air standards and equilibrated water samples. Rates of GPP will be calculated from $\delta^{17}O$ and $\delta^{18}O$ (Prokopenko et al. 2011) with corrections made for entrainment and mixing in both the vertical and horizontal dimensions (Howard et al. 2016, Nicholson et al. 2014).

NCP will be calculated from O_2/Ar ratios made on the same samples as the triple O_2 isotopes (sample precision = 0.2 per mil) and from a shipboard mass spectrometer that measures O_2/Ar ratios continuously in underway water with precision of 2 per mil on a timescale of seconds to minutes (Cassar et al. 2009). The continuous data will give rates of NCP with spatial resolution of several kilometers, while the discrete samples will allow for depth profile information required for correcting for physical transport, and calculation of NCP:GPP ratios. The O_2/Ar approach takes advantage of the similar solubility (Garcia & Gordon 1992, Hamme & Emerson 2004) and molecular diffusivity (Jähne et al. 1987) of both to quantify net biological production of oxygen, while correcting for physical processes (Craig & Hayward 1987, Emerson et al. 1991, Spitzer & Jenkins 1989). Solving mass balance equations, including estimates of gas exchange, allows the O_2/Ar ratios to be converted to rates of NCP (Hendricks et al. 2004, Juranek & Quay 2005, Reuer et al. 2007, Stanley et al. 2010). Corrections for vertical and horizontal mixing, especially important in this dynamic region, will be possible (Haskell et al. 2016, Jonsson et al. 2013) because of the frequent depth profiles and the wealth of physical oceanographic data collected as well as model simulations (section 4).

To use the rates from the gas tracer data to assess the model (Section 3.9) and to compare the gas tracer-based rates to NPP from the ^{14}C incubations, a photosynthetic quotient needs to be applied (to convert from O_2 to carbon). Laboratory studies with diatoms, chlorophytes, and cyanobacteria in a range of nutrient-limited conditions (Halsey et al. 2010, Halsey et al. 2013, Kana 1992) have shown that the amount of O_2 used for non-carbon producing reactions (i.e., the Mehler reaction, photorespiration, etc.) is 20-25% of the gross O_2 flux, resulting in a photosynthetic quotient of 1.25 to 1.33. This is less variable than the canonical photosynthetic quotients of 1.1 to 1.4 proposed by Laws (1991). We will apply photosynthetic quotients carefully, realizing the quotients may differ on the shelfbreak front and

elsewhere, and we will use the nutrient data, ^{14}C incubation results, and NCP:GPP ratio to assess the photosynthetic quotient for each location.

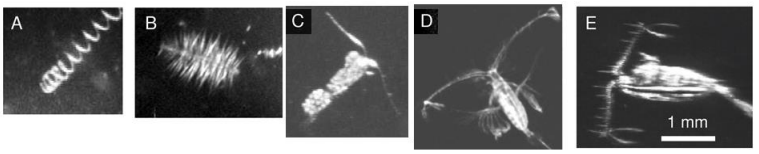

Fig. 8. Example images from the VPR: (A) helical diatom chain, (B) *Chaetoceros* chain, (C-E) copepods. Scale bar in (E) applies to all images.

3.7 Color Digital-Autonomous VPR (DAVPR)

The VPR is an underwater video system that images and identifies plankton and seston in the size range of 50 µm to >1 cm. It has been used extensively in shelf and slope waters to quantitatively map abundance patterns of both delicate and hardy plankton and seston over long distances (1000s of km) with high along-track spatial resolution (cm) (Ashjian et al. 2001, Davis et al. 1992, 2005, Gallager et al. 1996, Norrbin et al. 1996). The non-destructive nature of optical sampling allows us to observe, measure, and count fragile forms in their natural undisturbed state. Detailed intercomparisons of abundance estimates with those from more traditional sampling methods have established the accuracy of the VPR system (Basedow et al. 2013, Benfield et al. 1996, Broughton & Lough 2006).

The VPR can be deployed in a number of configurations, including both towed and profiling modes. Although the towed VPR-II system would have obvious appeal in this frontal environment, the abundance of fishing gear in this area makes the risk of entanglement too great. We will therefore opt for profiling mode with the color digital-autonomous VPR (DAVPR), which is available as shared use equipment at WHOI. The DAVPR fits inside the CTD-rosette frame, with the body clamped in place of a Niskin Bottle. It has a color digital video camera (UNIQ UC-1830CL, 1 megapixel, 10-bits/pixel, 15 frames s^{-1}) and a 20 cm diameter ring illuminator. The ring illuminator provides uniform dark field illumination, yielding better images of elongated and spinose forms. The DAVPR measurements will be used to quantify the abundance and distribution of large phytoplankton and mesozooplankton (Fig. 8), as well as marine snow. These measurements will be complemented by traditional vertical net tows with a ¼ m^2 MOCNESS (also available as shared use equipment) at selected stations.

3.8 Zooplankton grazing

Traditional zooplankton grazing studies have measured grazing by individual taxa, usually copepods, which were added to experimental containers with known phytoplankton concentrations, with the removal of cells over time used to estimate grazing (Campbell et al. 2005, Durbin & Durbin 1992, Frost 1972, Turner & Borkman 2005). While such studies are informative, they only assess grazing by the particular zooplankton species and stage and do not provide information on the impact of microzooplankton grazing (ciliates and heterotrophic dinoflagellates), which have been shown to be quantitatively significant grazers (Calbet & Landry 2004, Irigoien et al. 2005). Microzooplankton grazing is usually estimated with the dilution method (Landry & Hassett 1982). However, some assumptions of this technique are controversial (Agis et al. 2007, Calbet & Saiz 2013, Dolan et al. 2000, Schmoker et al. 2013, Stoecker et al. 2015). To assess the total grazing impact, the grazing of microzooplankton (< 200 µm) and mesozooplankton (> 200 µm) must be simultaneously measured.

These problems have been addressed in our recent studies of zooplankton grazing on dinoflagellates (Petitpas et al. 2015, Turner 2010), which involved incubating natural phyto- and zooplankton to evaluate net growth rates of a target phytoplankton species (*Alexandrium fundyense*). If concentrations of *A. fundyense* were significantly lower after incubation, then the decreases were attributed to grazing. Conversely, if post-incubation concentrations were significantly higher, this was interpreted as growth exceeding grazing. We will employ modified methods of Turner (2010) to measure grazing rates on all phytoplankton taxa in natural seawater samples. Changes in phytoplankton abundance after incubation will be quantified with a suite of methods to cover the full size range of the species assemblage (see below): conventional light microscopy of samples preserved in Utermöhl's solution (Petitpas et al. 2015), and counts from both the FCM and IFCB (Section 3.3). Changes in chlorophyll will also be quantified with standard fluorometric methods. We will conduct one experiment within each of the 12 transects, and the times and locations will coincide with the primary production measurements. Rate process measurements will be made on stations inshore of, offshore from, and at the front.

Grazing experiments will include 4 types of incubations: 1) whole plankton incubated under simulated *in situ* irradiance, 2) whole plankton incubated in the dark, 3) microzooplankton (< 200 µm) incubated under simulated irradiance, and 4) microzooplankton (< 200 µm) incubated in darkness. Dark treatments will minimize phytoplankton growth, allowing separation of grazing from growth of phytoplankton, and integrating circadian cycles in growth and feeding of heterotrophic protists (Jakobsen & Strom 2004). Incubations will be conducted under conditions similar to those of productivity measurements (section 3.5), with samples kept in a deck incubator at ambient temperature, and light in the grazing incubations reduced to 30% E_o with neutral density screens to avoid photo-oxidation of chlorophyll at high light. Incubations will run for 24 h. All treatments will include 3 separate carboys, with 3 replicate subsamples taken from each (432 samples per cruise) for post-incubation counts and identification of phyto-, microzoo- and mesozooplankton.

All samples will be analyzed to quantify and identify phytoplankton from picoplankton to large chain-forming diatoms, as well as their grazers. Changes in abundances of picoplankton and small nanoplankton will be measured by FCM at sea. Changes in microplankton, including chain-forming diatoms and protozoa, will be quantified with the IFCB at sea and conventional microscopy on the Utermöhl-preserved samples ashore. Abundances of microzooplankton and mesozooplankton grazers during incubations will be quantified with conventional microscopy. This will allow estimates of losses from grazing, and growth over and above losses, both for individual phytoplankton taxa as well as for the entire assemblage.

At selected stations where rates are being measured, we will also perform comparisons of the aforementioned grazing studies with the "two-point" dilution technique (Chen 2015 and references therein). This will help to place the results of our grazing studies within the context of the dilution technique, which despite emerging caveats, is still widely used.

3.9 Data synthesis

For each of the cruises, we will time-average the physical and biological data from the 12 transects centered on the front, along with the mooring and mobile asset data from the Pioneer Array. This will help remove high-frequency signals, allowing us to obtain a robust representation of the temporal mean structure of physical and biological properties across the front. We anticipate the plankton community responses to changes in physical circulation will take place over time scales longer than the 1-3 day synoptic scales. Thus, a two-week mean will help reveal how the frontal circulation is related to persistent characteristics of the plankton communities. Data from the individual transects and the differences among them will provide a measure of the temporal variability of the frontal circulation and help quantify how synoptic physical processes affect the plankton.

The FCM and IFCB measurements will enumerate each phytoplankton cell P_i and its associated volume V_i within a given sample, with V_i estimated from light scattering for the FCM (Laney & Sosik 2014) and image analysis for the IFCB (Moberg & Sosik 2012). The carbon content of each cell will be estimated with literature based carbon-to-volume relationships according to Menden-Deuer and Lessard (2000): $\log(C_i) = \alpha + \beta \log(V_i)$; they showed that large diatoms follow a different function than other protists (presumably due to their relatively large vacuoles), so IFCB images will be used to determine the appropriate conversion for each cell type. C_i values can be summed to estimate phytoplankton carbon in size classes of diameter d (µm) that reflect the ecosystem model structure:

$$C_{pico\_nano} = \sum_{i,d<20} C_i \qquad C_{micro} = \sum_{i,d>20} C_i \qquad C_{total} = \sum_{i} C_i$$

POC measurements provide a check on the phytoplankton carbon estimates, as we expect $C_{total} < POC$ because there are other forms of carbon included in POC such as zooplankton and detritus. The FCM/IFCB-derived phytoplankton carbon measurements will also be used together with chlorophyll measurements to compute C:Chl ratios, which will help constrain that parameter in the model.

Light and dark incubations will be used to measure temporal changes in phytoplankton carbon:

$$\left(\frac{dC}{dt}\right)_{light} = growth - grazing \qquad \left(\frac{dC}{dt}\right)_{dark} = -grazing$$

where the total phytoplankton carbon is broken down into the two different size classes. FCM and IFCB measurements in the initials and finals will permit expression of the inferred rates in terms of carbon

$$\frac{dC}{dt} = \frac{(\sum C_i)_{final} - (\sum C_i)_{initial}}{\Delta t}$$

thus providing the opportunity to check for consistency between the incubation-derived growth rates and the ^{14}C productivity measurements

$$\left(\frac{dC}{dt}\right)_{light} - \left(\frac{dC}{dt}\right)_{dark} = growth = \mu C = ?\ {}^{14}C$$

where μ is the specific growth rate for phytoplankton. Changes in chlorophyll during the incubations, normalized to phytoplankton carbon from the FCM/IFCB, will provide another consistency check.

Growth and grazing (g) rates will be estimated for different size classes of phytoplankton:

$$\left(\frac{dC_{micro}}{dt}\right)_{light} - \left(\frac{dC_{micro}}{dt}\right)_{dark} = \mu_{micro} C_{micro} \qquad \left(\frac{dC_{micro}}{dt}\right)_{dark} = g_{micro} C_{micro}$$

Thus a suite of rate estimates will be available to constrain the model (section 4):

Volumetric photosynthetic rate: size-fractionated ^{14}C	[g C m^{-3} d^{-1}]
Specific phytoplankton growth rates: μ_{total}, μ_{pico_nano}, μ_{micro}	[d^{-1}]
Volumetric grazing rate: $\left(\frac{dC_{total}}{dt}\right)_{dark}$, $\left(\frac{dC_{pico\_nano}}{dt}\right)_{dark}$, $\left(\frac{dC_{micro}}{dt}\right)_{dark}$	[g C m^{-3} d^{-1}]
Specific grazing rates: g_{total}, g_{pico_nano}, g_{micro}	[d^{-1}]
Gross primary production	[g C m^{-2} d^{-1}]
Net community production	[g C m^{-2} d^{-1}]

Volumetric rates will be converted into nitrogen units via the Redfield ratio, constrained by C/N measurements of particulate material. Rates of GPP and NCP will be used as a diagnostic tool to assess the model: GPP will provide an upper limit on modeled photosynthesis, and NCP rates will provide a check on the balance of primary and secondary production. Note that the gas tracer measurements will yield estimates only for the mixed layer; the ^{14}C incubation profiles will be used to scale this mixed layer production for the entire euphotic zone. Because the model only tracks particulate organic carbon, whereas the gas tracer-based rate measurements will include contributions of dissolved organic carbon (DOC), we will assume that DOC fuels ~20% of NCP (Carlson et al. 2010). A recent study has shown DOC production is a near constant fraction of new production and thus by extension of NCP (Romera-Castillo et al. 2016).

In addition to the rate measurements providing constraints on the model (section 4), incubation-based rate information will be extrapolated to larger spatial and temporal scales. Specifically, to expand productivity estimates over similar time and space scales of biomass and composition measurements, a simple bio-optical model will be used to generate productivity from chlorophyll derived from gliders and other platforms. Near-surface quenching of fluorescence during daytime will be corrected with procedures developed from other glider experiments (Kaufman et al. 2014). Using corrected chlorophyll data, productivity will be estimated from a model that combines PAR data, photosynthesis versus irradiance responses, and temperature to estimate productivity (Behrenfeld & Falkowski 1997). Estimates will also be made from satellite algorithms, but we recognize that sub-surface biomass maxima (such as those which might occur) will not be adequately resolved by such models. Hence, a combination of these methods will allow for primary production to be estimated on a variety of temporal and spatial scales. We will take a similar approach to extrapolating the grazing measurements, applying the biomass-normalized rates to biomass estimates from the VPR and IFCB/IFCB-S. These extrapolations will be less spatially extensive than those for primary production facilitated by glider data and satellite imagery, but they will help to extend the scope of our observations.

To evaluate the undersampling hypothesis H_{4b}, we will construct long-term seasonal means of the frontal structure from the entire record of Pioneer Array measurements. Although this will be straightforward for physical oceanographic variables, it will be more challenging for bio-optical instruments for which intercalibration is an issue (Alkire et al. 2012, Briggs et al. 2011, Johnson et al. 2009). We will work directly with the OOI team to make best use of pre- and post-deployment calibration

information to ensure that our long-term seasonal means of the cross-frontal structure of fluorescence and backscattering are as accurate as possible. We will also examine the possibility that acoustic data from the Pioneer Array can be used to make quantitative estimates of zooplankton biomass, or at least the seasonal variations thereof (Flagg & Smith 1989, Heywood et al. 1991).

4. Modeling, hypothesis testing, and overall synthesis

Our strategy builds on the foundation of prior models of both the physics and biology of the region. For example, Chen and He (2010) describe hindcasting studies of the circulation in the Middle Atlantic Bight / Gulf of Maine (MABGOM) region. The MABGOM model (Fig. 9) is embedded within the existing data assimilative North Atlantic Hybrid Coordinate Ocean Model (HYCOM; 2007, Chassignet et al. 2003) via a one-way nesting technique (Blayo & Debreu 2006, Marchesiello et al. 2001). Hindcast simulations accurately depict the mean shelf circulation and features of the synoptic variability (Chen & He 2010, Chen et al. 2014). Nested within the MABGOM domain is a high-resolution (1 km) model of the shelfbreak (Fig. 9b), in which a planktonic ecosystem model has been run (He et al. 2011). This inner nest builds on experience from prior nested models of the inner shelf (He & Wilkin 2006, Wilkin 2006), and is described in detail in Chen and He (2010). Although highly relevant to the proposed research, this set of models is not an ideal configuration for our application. Nonetheless, the results of these studies do provide guidance for our specific implementation.

The model we plan to use will build on those implemented by PI Zhang in a recently completed project (see section 6). Like prior models of the region, the New England Shelf Ecosystem and Circulation (NESEC) Model is based on the Regional Ocean Modeling System (ROMS; Shchepetkin & McWilliams 2005). A key attribute of the NESEC implementation is the capability to assimilate data, which will provide realistic estimates of the ocean's physical state on which our coupled physical-biological simulations will be based. ROMS contains algorithms for four-dimensional variational assimilation (4DVAR; Moore et al. 2011a, b, c), which uses observations to correct model initial and boundary conditions and surface forcing, while maintaining the dynamical balance of the system. An appeal of this methodology is that the resulting fields can feed into the term balance analysis, which is important for computing the tracer fluxes associated with physical/biological processes. ROMS 4DVAR has been applied in several coastal areas, including the New York Bight (Zhang et al. 2010). It is currently being used in a MAB model (ESPRESSO; Wilkin & Hunter 2013) for real-time forecasting and hindcasting in a large regional domain that includes the NESEC model domain (Fig. 3).

4.1 Regional 3D hydrodynamic simulations and state estimation

Horizontal resolution of the NESEC model will be 1 km, well below the deformation radius in the region (5-10 km). The model will have ~80 vertical layers. Atmospheric forcing will be specified from the operational North America Mesoscale (NAM) model; oceanic boundary conditions will be provided by ESPRESSO. The simulation will span 2018-2019, covering all cruises. The model will first be tuned to reproduce the regional circulation pattern depicted by the existing observations, so the data assimilation system can be built upon the best possible background "free-run" solution. The annual and seasonal mean of the shelf circulation from this free-run will be compared with climatology (Linder & Gawarkiewicz 1998, Linder et al. 2004, Zhang et al. 2011) and linear models (Lentz 2008a, b).

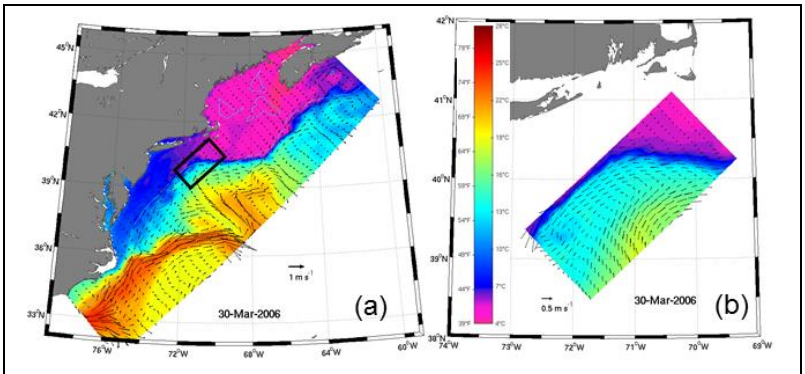

Fig. 9. Simulated sea surface temperature fields on March 30, 2006 (Chen & He 2010). Surface velocity vectors are shown in both the shelf-wide model (a) and its nested 1-km resolution shelfbreak model (b). Domain of the inner nest is depicted by the solid black line in (a).

We will then use 4DVAR data assimilation to correct the fine-scale processes in the model and to provide an improved ocean state for analysis of the frontal dynamics and the hydrodynamic context for 3D

physical-biological simulations. We will first test the linearization embedded in the tangent linear and adjoint models of the 4DVAR system, which puts a constraint on the length of the individual data assimilation window. Based on our experience, we expect the data assimilation window to be 5-7 days. Data assimilative hindcasts in the NESEC domain will thus be cast in consecutive overlapping windows with a one-day offset as in Zhang et al. (2010). We will then form a continuous reanalysis of the ocean state by concatenating the last day of each of the overlapping windows. This approach diminishes the issue of initialization shocks at the start of each analysis window. With the 4DVAR machinery, we plan to assimilate all available physical measurements, both *in situ* (Pioneer Array and our cruise) and remotely sensed (HF radar-measured surface currents and satellite-measured SST). We will coordinate this effort with our long-term collaborator J. Wilkin (Rutgers) who is funded by NSF (OCE-1459646) to conduct a model-based synthesis of Pioneer Array physical data to infer cross-shelf fluxes, frontal variability, and characteristics of the array. Our interactions will include sharing setups of the model and 4DVAR system, as well as data streams for model initialization, assimilation, and validation.

Our hindcast 4D physical fields will facilitate several lines of inquiry into processes occurring in the vicinity of the shelfbreak. To begin with, analysis of the corrections that 4DVAR makes to open boundary conditions and surface forcing will shed light on limitations of the larger domain ocean model and NAM model in the NESEC area, respectively. Data from the Pioneer Array will be particularly valuable for evaluating these corrections, both in terms of the forcing (meteorological measurements from moorings) and the boundary conditions (glider data). Secondly, the residual differences between simulated and observed properties will provide guidance as to the most important deficiencies of the interior model itself. As such, we will analyze those residuals, identify any coherent patterns, and undertake model improvements as warranted. Thirdly, we will analyze the model output to reveal the characteristic frontal dynamics, including frontal meandering and vorticity dynamics, and the effects of these 3D processes on frontal upwelling, bottom boundary layer detachment, and subsequent transport pathways of those detached fluid parcels. This will provide a quantitative basis on which to assess the relative importance of the four upwelling mechanisms that comprise hypothesis H_1.

4.2 Regional 3D physical-biological simulations

As with the hydrodynamic component, we will build on prior biological models of the region. For example, the seven-component planktonic ecosystem model of Fennel et al. (2006) was implemented for the North East North American (NENA) shelf, nested within the same HYCOM North Atlantic basin-scale model described above. The 10 km horizontal resolution of the NENA model is considerably coarser than will be used in the proposed research, yet comparisons with measurements presented in Fennel et al. (2006) and Hofmann et al. (2008) show that the model captures the large-scale low-frequency characteristics of the region. Modeled mean seasonal cycles of nitrate, ammonium, surface chlorophyll, and primary production generally fall within one standard deviation of observations. Lehmann et al. (2009) found that a more complex ecosystem model can provide even more skillful representation of observations in this region.

The Lehmann et al. (2009) model (based on Lima and Doney (2004)) is well suited to the proposed research, as it differentiates between two "functional groups" (Hood et al. 2006) of phytoplankton: small (picoplankton) and large (diatoms). Such formulations have been included in a number of ecosystem models (Aumont et al. 2003, Chai et al. 2003, Dugdale et al. 2002, Dutkiewicz et al. 2005, Gregg et al. 2003, Ji et al. 2006, Jin et al. 2006, Kishi et al. 2007, Moore et al. 2004). For the present purposes, we will expand the treatment of zooplankton from one type to two, such that microzooplankton and mesozooplankton will be explicitly represented to allow direct comparisons with data from the IFCB and VPR. We will use the measured rates of primary production and grazing, as well as the NCP and GPP estimates to constrain rate processes of the model (see section 3.9 above). To provide initial and boundary conditions for the high-resolution NESEC domain, we will run the biological component in the ESPRESSO model, specifying the initial and boundary conditions with the approach described in Fennel et al. (2006). Given the distance between the boundaries of the ESPRESSO model and the embedded NESEC model, we expect biological constituents to be dynamically adjusted prior to fluid entering into the interior subdomain. We will not conduct data assimilation with either biological model. Skill of the

NESEC biological solutions will be evaluated against our cruise data, with particular emphasis on plankton size structure and composition, as well as nutrient and biomass distributions. Robustness of the solutions will be quantified via parameter dependence and sensitivity analysis.

After quantifying the skill of the model in simulating the observed distributions, we will diagnose the solutions in detail. Initially we will characterize the simulated nutrient, phytoplankton and zooplankton distributions in the frontal area to test hypotheses H_2 – H_{4a}. Term balances in the model solutions will be examined in conjunction with the physical and biological observations to understand how frontal circulation affects the productivity and taxonomic composition of the plankton. We will then compute the annual and seasonal along-shelf averaged biomasses of small and large phytoplankton, and small and large zooplankton, and compare to the 2D model results (Zhang et al. 2013). This will allow us to investigate the effects of 3D structure (e.g., cross-shelf meandering of the front) on the climatological cross-shelf distributions of biomass and productivity. Time series of nutrient and biomass fluxes across the shelfbreak will be computed, and their seasonal variation and vertical scales will be examined. EOF analyses on the nutrient and biomass fluxes will be used to check whether they have systematic patterns in space and/or time that can be explained by changes in external forcing. To address H_{4b}, these analyses will be conducted on both seasonal and synoptic time scales to elucidate the degree to which episodic events affect the mean patterns in phytoplankton in and around the front. We will resample the model with space/time resolution typical of the climatology to quantify the degree to which frontal enhancement is captured by such observations, thereby providing a model-based assessment of H_{4b}.

5. Broader impacts

The broader impacts of this project fall into three main categories: 1) "advance discovery and understanding while promoting teaching, training and learning", 2) "broad dissemination to enhance scientific and technological understanding", and 3) "benefits to society".

We will promote teaching and training by incorporating the approaches and results from the proposed studies into a graduate course in physical/biological interactions that Dr. McGillicuddy co-teaches with Prof. Glenn Flierl in the MIT/WHOI Joint Program. The proposed research will also involve graduate and undergraduate students. We anticipate entraining at least 10 undergraduates among the four institutions, drawing from the WHOI Summer Student Fellowship and NSF REU programs, the Wellesley Summer Science Center Research Program, and the UMassD internship program. These programs specifically target underrepresented groups, including first generation college students, and we will seek participants within this pool of candidates who are outside of typical science career paths.

We plan to convey our work to public audiences through open lectures, interviews, and production of at least one article specific to the broader question of the importance of frontal processes to ecosystems. Such an article is proposed for *Oceanus,* a twice-yearly publication by WHOI with a print circulation of 7,000. The magazine also publishes an average of nearly one article per week on its home page, which averages ~45,000 visitors per month. We also plan a three-part video documentary to be produced by Science Media, a company that has produced several such pieces for NSF-sponsored research. A videographer will participate in each of the three cruises, crafting three episodes that focus on the following topics: (1) interdisciplinary science of a highly productive frontal region: physics, chemistry, and biology; (2) use of the OOI assets together with shipboard observations for adaptive sampling of highly dynamic phenomena; and (3) the impact of what is learned on stewardship of living marine resources, with specific connection to the fishing community.

Lastly, better understanding of the dynamics of the shelfbreak front will benefit society by providing an improved scientific basis for stewardship of an important region for both commercial fisheries and biodiversity. Results from the field program will be shared with the Commercial Fisheries Research Foundation (CFRF), a non-profit established by commercial fishermen in southern New England. McGillicuddy and Sosik participated in a joint workshop with CFRF in January 2013 (Gawarkiewicz et al. 2013) that highlighted fishermen's concerns about rapid ecosystem change and their strong support for basic research in the region. The workshop prioritized research objectives for the shelfbreak ecosystem and highlighted both nutrient distributions and trophic interactions as areas needing further basic field measurements. CFRF holds frequent workshops bringing the academic community together with

fishermen and results will be shared at either an appropriate workshop or a CFRF board meeting.

6. Results from prior NSF support

Note: publications listed in section D, marked with a symbol for each PI (,#,@,&,%,^).*

*__McGillicuddy, D.J.__, Davis, C.S., Dyhrman, S.T., and J.W. Waterbury**.** OCE-0925284 ($1,321,055; 12/01/2009 - 09/30/2013), *Quantification of Trichodesmium spp. vertical and horizontal abundance patterns and nitrogen fixation in the western North Atlantic*. ***Intellectual merit:*** We tested the hypothesis that populations of *Trichodesmium* spp. deep in the euphotic zone are actively fixing nitrogen, contributing a significant source of new nitrogen heretofore underestimated. Seven refereed publications have resulted thus far, with more in preparation. ***Broader impacts:*** The project provided training for 1 postdoctoral fellow, 3 graduate students, 2 undergraduates, and 1 high school student. An online "citizen science" activity was developed in which participants enumerate *Trichodesmium* images from VPR data.

Petitpas, C.M.: no prior NSF support.

#**Smith, W.O.** ANT-0944254 ($365,203; 07/01/2011 - 06/30/2015), *Collaborative Research: Impact of Mesoscale Processes on Iron Supply and Phytoplankton Dynamics in the Ross Sea*. ***Intellectual merit:*** Primary findings were 1) a detailed annual Fe budget indicated the importance of deep-water sources for growth 2) a previously poorly described stage of *Phaeocystis* was observed using the VPR; and 3) spatially variable mixed layers result in substantial spatial variations in biomass. Thus far the project has resulted in 8 peer-reviewed publications with others in preparation; numerous national/international presentations given. ***Broader impacts***: One graduate and two undergraduate students were supported.

Olson, R.J., @**Sosik, H.M.** OCE-1130140 ($934,340; 9/15/2011-8/31/2016), *Collaborative Research: Enhanced Imaging Flow Cytometry for Plankton Studies via Acoustic Focusing and Emulsion Microfluidics*. ***Intellectual Merit:*** We developed new capabilities that integrate with the automated imaging-in-flow cytometer Imaging FlowCytobot: acoustic focusing to concentrate particles into the center of the sample stream above the flow cell; physical sorting of imaged cells; and automated live-cell staining for protozoans. To date, the project has resulted in 2 publications, 1 patent application, and over 20 presentations. ***Broader Impacts:*** training two undergraduates, enabling two PhD theses, advancing community technologies, and outreach activities through the Zephyr Education Foundation.

&**Stanley, R.** and A. Spivak: OCE-1233678. (8/12 to 7/16) "*Eutrophication Effects on Sediment Metabolism and Benthic Algal-bacterial Coupling: An Application of Novel Techniques in a LTER Estuary*" ($384,493 to Stanley). ***Intellectual Merit:*** We probed effects of increased nutrient loading in salt-marsh creeks and ponds and found increased rates of gross primary production but more negative net community production, a shift in active members of microbial communities, and light respiration rates double those of dark, as described in 3 published papers. ***Broader Impacts****:* We mentored 13 female undergraduate students (including under-represented minorities and first generation college students) and one doctoral student, and provided information on managing an important economic resource.

%**Turner, J.T.** subaward from Anderson, D.M., Richlen, M. and Ralston, D. OCE-0430724 ($540,596.00; 09/15/2011 - 08/31/2014), Microbial influences on *Alexandrium* populations. ***Intellectual merit***: We performed whole-community incubation experiments to assess net zooplankton community grazing impact on *Alexandrium* populations in the Nauset Marsh System (NMS) on Cape Cod, resulting in a publication in *Harmful Algae*. ***Broader impacts***: The project provided the basis for a portion of the dissertation research for 1 doctoral student. Environmental and biological data contributed to the management of resources within the NMS, which is part of the Cape Cod National Seashore.

^**Zhang, W.G.** and G. Gawarkiewicz: OCE-1129125, $590,249; 09/01/2011–08/31/2015, Dynamics of frontal meandering and related exchange processes at the shelfbreak south of New England. ***Intellectual Merit***: Five journal articles were published on the following topics: 1) shelfbreak variability, 2) an unusual case of Gulf Stream influencing the shelfbreak, 3) mechanisms of frontal meander, 4) dynamics of warm-core ring water onshore intrusion, and 5) the influence of persistent shelfbreak upwelling on local biological productivity and the impact of grazing on phytoplankton biomass. ***Broader Impacts***: We communicated shelfbreak oceanography to general public in New Bedford Fish Expo and a Shelfbreak Ecosystem Workshop, and this project supported the mentoring of two postdocs.

Highlighted pubs from prior support section

McGillicuddy
(Davis et al., submitted; Haley and Dyhrman, 2013; Luo et al., 2012; McGillicuddy, 2014; Olson et al., 2015a; Olson et al., 2015b; Rouco et al., 2014)

Smith
(Mosby and Smith, 2015, Mosby and Smith, 2016; Smith et al., 2014a; Smith et al., 2014b; Smith and Donaldson, 2015; Smith and Jones, 2014; Smith et al., 2016; Jones and Smith, 2016)

Sosik
Brownlee et al.
Lambert et al.

Stanley
Kearns et al., 2016, Spivak and Ossolinksi, 2016, Spivak and Reeve, 2015

Turner
Petitpas et al. 2015

Zhang
Todd, R. E., G. G. Gawarkiewicz, and W. B. Owens (2013), Horizontal scales of variability over the Middle Atlantic Bight shelfbreak and continental rise from finescale observations, *J. Phys. Oceanogr.*, *43*, 222-230, DOI: 10.1175/JPO-D-12-099.1.
Gawarkiewicz, G. G., R. E. Todd, A. J. Plueddemann, M. Andres, and J. P. Manning (2012), Direct interaction between the Gulf Stream and the shelfbreak south of New England, *Sci. Rep.*, *2*, 553, DOI: 10.1038/srep00553.
Zhang, W. G., and G. G. Gawarkiewicz (2015), Length-scale of the finite-amplitude meanders of shelfbreak fronts, *J. Phys. Oceanogr.*, *45*(10), 2598-2620, DOI: JPO-D-14-0249.1.
Zhang, W. G., and G. G. Gawarkiewicz (2015), Dynamics of the Direct Intrusion of Gulf Stream Ring Water onto the Mid-Atlantic Bight Shelf, *Geophys. Res. Lett.*, *42*, 7687-7695, DOI: 10.1002/2015GL065530.
Zhang, W. G., D. J. McGillicuddy, and G. G. Gawarkiewicz (2013), Is biological productivity enhanced at the New England Shelfbreak Front?, *J. Geophys. Res.*, *118*, 517–535, DOI: 10.1002/jgrc.20068.

7. Facilities, Equipment and other Resources

Laboratory:

Both the Accuri C6 flow cytometer and the Color Digital-Autonomous VPR (DAVPR) will be provided at no cost to the project via the shared use equipment pool of the WHOI Biology Department.

Several standard Imaging FlowCytobot (IFCB) instruments are available in the Sosik laboratory to support time series (e.g., MVCO) and process cruise observations. In addition, there is one recently developed Staining IFCB that expands capability to discriminate live microplankton cells that may not exhibit chlorophyll fluorescence. One standard IFCB and the Staining IFCB will be available at no cost for the cruise work proposed for this project.

In the Sosik laboratory, we will have access to facilities and equipment to support maintenance and evaluation of instruments in preparation for the proposed cruise operations. These include a wide variety of electrical, optical, electronic equipment and testing devices, including power supplies, function generators, digital oscilloscopes, diode lasers, LEDs, photomultipliers, amplifiers, and PIC microprocessor systems. We also have extensive phytoplankton culturing facilities and a phytoplankton culture collection that can be used to evaluate instrument performance during testing and configuration.

In the Stanley laboratory at WHOI, there is a Thermofisher 253 Isotope Ratio Mass Spectrometer configured specifically for measuring triple oxygen isotopes and O_2/Ar ratios. The attached automated processing line makes use of a custom-made cryogenic trap, Neslab recirculating chillers, GC column, refrigerated bath, turbomolecular pumps, and mechanical pumps. The entire system is under automated control and can be checked from the internet. Sample precision on that system is typically 5 per meg for $^{17}\Delta$, 0.01 per mil for $\delta^{17}O$, and 0.008 per mil for $\delta^{18}O$.

Our nutrient samples will be run at WHOI's Nutrient Analytical Facility. The facility utilizes several state of the art methods and instruments for quantifying bio-element concentrations in environmental samples. The facility operates a SEAL AA3 four-channel segmented flow analyzer to determine dissolved nutrient concentrations in aquatic ecosystems ranging from groundwater to the open ocean. It offers a high sample throughput coupled with simple and rapid method changeover to maximize productivity in determining nutrients including: ammonium, nitrate, nitrite, orthophosphate, silicate, and total dissolved nitrogen. The methods used for analysis are USEPA approved.

Clinical: N/A

Animal: N/A

Computer: The computational infrastructure of Dr. McGillicuddy's laboratory consists of a network of eight Dell Precision T7400n Workstations operating Redhat Enterprise Linux 5.2, each unit with two quad core Xeon processors running at 3.00GHz, 8 GB memory, and 500 GB disk space. A 2.6TB and a 3.4TB Raid server are available for local storage of model results and visualizations. These systems are sufficient to carry out the proposed data analysis. Computational infrastructure in the Sosik laboratory includes two Dell Precision T7500/7600 six core workstations with >3TB storage for routine data analysis and access; and, for more demanding image analysis and classification tasks, three Dell R710 PowerEdge servers (rack mounted), each with two 6-core Xeon X5660s 2.8GHz processors, 72 GB of RAM, and 5TB of local disk space. The R710 servers are connected to a BackBlaze Storage Pod with 120TB installed disk storage and to one another via dedicated 10 GigE switch. Zhang owns a portion of a WHOI community computer cluster (288 out of the total 2160 computing cores), and he has access to the

entire cluster through a cluster queuing system. Should this proposal be successful, Zhang will apply for time at one of the national supercomputer centers, to supplement WHOI computer resources.

Office: All personnel have adequate office space.

Other resources: A wide range of shop services and facilities is available to WHOI staff including a precision machine shop, carpentry shop, and graphics services. WHOI's Computer and Information Services (CIS) group provides computer services including technical support, consulting and applications programming services for distribution and central computing systems used by the WHOI community.

8. Data management plan

All data collected during this project will be managed by the Biological and Chemical Oceanography Data Management Office (BCO-DMO) located at WHOI. The BCO-DMO will also handle submission of the data to NODC for final archiving at the end of the project. We will meet with BCO-DMO staff during the first six months of our project to discuss details associated with each of our data types and define protocols for producing appropriate data format, documentation of quality control, and metadata. BCO-DMO staff will also provide guidance on best practices for cruise data management (cruise reports and sampling event logs) and facilitate the publication of our results after the cruise. Underway data are critical to this project, and we are pleased to contribute standard underway ship-based measurements as well as our own measurements as part of the UNOLS central data repository at http://www.rvdata.us/catalog/, managed by the Rolling Deck to Repository (R2R) project.

While access to data will be limited to the participating investigators for an initial period of time, public access to all data and supporting documentation (metadata) will be granted within two years. Data and metadata from this project will be available as part of the larger BCO-DMO data system. The ability to integrate results from this project with those from prior research will greatly enhance the value of the data to be collected and ensure its central maintenance and accessibility into the future.

Dr. McGillicuddy has extensive experience with BCO-DMO staff, having worked closely with them in management of data from the NSF-sponsored EDDIES project (OCE-0241310), Quantification of *Trichodesmium* spp. vertical and horizontal abundance patterns and nitrogen fixation in the western North Atlantic (OCE-0925284), as well as a collection of data sets dealing with harmful algal blooms in the Gulf of Maine:

http://www.bco-dmo.org/project/2048
http://www.bco-dmo.org/project/2104
http://www.bco-dmo.org/project/2118

Results from three of Dr. McGillicuddy's modeling projects are also archived there:

http://www.bco-dmo.org/dataset/3198
http://www.bco-dmo.org/dataset/3195
http://www.bco-dmo.org/project/473687

and we will do the same for the modeling results generated by the present project. We will also supply model output (or links thereto) to the two relevant regional components of NOAA's Integrated Ocean Observing System: the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS), and the Mid-Atlantic Regional Coastal Ocean Observing System (MARCOOS).

Image and image product data sets – Because of the unique challenges in effectively sharing the large image data sets and the analysis products associated with them, we will also provide specialized access to these observations. This will be accomplished with mechanisms already established in the Sosik laboratory for rapid and easy web-based access to these types of data. This access includes not only raw images (~several GBytes day^{-1}), but also the metadata associated with each image (e.g., date/time, as well as fluorescence, light scattering, location in camera field, etc.) and the routine image products produced from our analysis pipeline (masks to identify target pixels, extracted features and biomass metrics, taxonomic classification results for each image). This will follow the pattern currently implemented for IFCB imagery collected at MVCO; see http://ifcb-data.whoi.edu/ where images and associated metadata are openly accessible through html, PNG, JPG, RDF, XML, and other standard formats via web services.

Budget Information

The Woods Hole Oceanographic Institution (WHOI) is a non-profit [501c(3)] research and education organization subject to the cost principles of 2 CFR 200. WHOI Principal Investigators are responsible for conceiving, funding and carrying out their research programs. Senior Personnel are expected to raise 12 months of support for themselves and their staff by writing proposals and obtaining sponsored research grants and contracts from a variety of sources. Some teach voluntarily in WHOI's Joint Program, but support for this is limited. NSF has confirmed to WHOI that salary support from grants beyond 2 months per year can be justifiable for these Principal Investigators.

The rates included in the proposal are negotiated with our cognizant government agency.

For 2017 and beyond, WHOI has a negotiated rate agreement with the Office of Naval Research and uses the method of allocation of indirect costs to Modified Total Direct Costs (MTDC). The normal exclusions contained in 2 CFR 200.68 (MTDC) apply, as well as the following cost categories; ship use, submersible use, vessel charters and ship fuel.

A proposed labor month is equal to 152 hours or 1824 hours annually versus 2080 hours (40 hours/week for 52 weeks). The difference is for vacations, holidays, sick time, and other paid absences, which are included in the Paid Absences calculation. WHOI cannot "waive" or reduce overhead rates on any sponsored research project due to the structure of our negotiated rates with our cognizant government agency (Office of Naval Research). When a program sets limits on overhead, WHOI must use Institution unrestricted funds to pay the unfunded portion of the overhead costs.

Budget Justification

Salaries: As lead investigator, Dr. McGillicuddy will oversee all aspects of the project. His group's responsibilities include acquisition and analysis of (1) hydrography, (2) nutrients, and (3) Video Plankton Recorder (VPR) data at CTD stations. Dr. McGillicuddy requests two months salary in year one and one month in each of years two and three. He will serve as chief scientist in all three cruises. O. Kosnyrev will participate in all of the cruises and serve as Dr. McGillicuddy's primary assistant for post cruise data analysis and visualization. Ms. Kosnyrev will also be responsible for submission of our data to BCO-DMO as described in our data management plan. Salary support requested for Ms. Kosnyrev to carry out these tasks amounts to four months per year in years one and two, followed by six months in year three.

Salary support in the amount of two months per year is requested for PI Sosik to oversee the phytoplankton observation and analysis components of the project, including participation in cruises. Four months salary per year is requested in years 1 and 2 for Research Assistants E. Peacock and E. Crockford to maintain and prepare instrumentation and laboratory apparatus and supplies required for phytoplankton and pigment observations and to conduct routine sampling on cruises. Their time allocations are increased to seven months in year three to perform supervised data processing and analysis of the observations. Sosik will supervise a full time Graduate Research Assistant pursuing a Ph.D. in the MIT/WHOI Joint Program. The student (TBA) will participate in the proposed cruises, and focus his/her thesis research on analysis and interpretation of the IFCB observations.

PI Rachel Stanley (Wellesley College) will supervise the gas tracer components of the project. Salary support for her is requested through the Wellesley component of the proposal. Z. Sandwith will participate in all the cruises, where she will be in charge of the equilibrator inlet mass spectrometer and will collect samples for triple oxygen isotopes. Additionally, Sandwith will run the triple oxygen isotope samples on the mass spectrometer system at WHOI. For these tasks, 5.5 months of salary support is requested in year 1, 4.5 months in year 2, and 0.5 months in year 3.

PI Zhang requests four months salary support per year to (1) participate in the cruises, (2) implement the 4DVAR data assimilation system, (3) conduct the realistic physical and biological simulations, (4)

conduct model-data comparisons, (5) use the model results to diagnose the various mechanisms of upwelling, and (6) analyze results of the biological simulations and sensitivities of the results to various biological parameters.

Two weeks of support for S. Barkley is requested each year to assist with grant management, manuscript preparation, travel and cruise logistics, and preparation of project reports. These tasks are specifically related to the project and are not supported by overhead.

Equipment: Allowances are requested for an 18TB (usable space) Raid file server to store the model output locally for dynamical analysis.

Travel: Funds are requested for team members to attend national scientific meetings to report on the results of the project. For budgeting purposes, the estimated cost of attending a meeting in San Francisco, CA (e.g., AGU) is specified for domestic travel ($4,161 per trip; one person in years 1 and 2 and three persons in year 3, seven days per trip) and the Ocean Sciences meeting in New Orleans, LA ($2,729 for one person in year 2 for seven days). Estimates for airfare are based on rates currently available on Expedia for refundable tickets and include an allowance for baggage and agent fees. Ground transportation costs include rental car(s) and transportation to/from the airports. Meeting registration fees are based on previous meetings. Per diem expenses are based on rates currently available via the GSA website (http://www.gsa.gov/portal/category/21287) for domestic travel.

Other Direct Costs:

Supplies: The network of workstations currently available in the laboratories of PIs McGillicuddy, Sosik, and Zhang will be sufficient for the research proposed herein. However, allowances for computer supplies specific to the proposed work (CPU upgrades, backup units, toner cartridges, batteries and electronic storage devices) are requested to keep this infrastructure current ($8,000 year 1, $2,500 year 2, $2,500 year 3). We request funds ($6,000 year 1 and $4,000 year 2) to purchase laboratory supplies required for sample collection and analysis (e.g., bottles, filters, vacuum pumps, reagents) and instrument maintenance (e.g., cables, replacement syringes and pumps). Additionally, funds are requested for consumable supplies for the equilibrator inlet mass spectrometer during the cruise, such as equilibrator cartridges, filters, tubing, filaments, etc. ($3200 in year 1, $2100 in year 2). In year 1, funds are also requested for a replacement gear pump for the equilibrator inlet mass spectrometer ($1200). Supplies required for analyzing the triple oxygen isotope mass spectrometer include a filament and gold gasket for each set of cruise samples (oxygen is harsh on filaments and makes them need to be replaced more often that is common for analysis of other gases) ($2600 in year 1, $1300 in year 2), and gases such as liquid nitrogen, compressed nitrogen and helium ($2078 in years 1 and 2). Funds are also requested for sampling supplies for the triple oxygen isotope samples (torrlube grease, tubing) ($300 in year 1, $150 in year 2) and for miscellaneous supplies needed during analysis (turbo pump wicks, rough pump oil, vaccum grease, etc.) amounting to $500 in year 1 and $300 in year 2.

Publications: Publication costs are requested to disseminate the results in peer-reviewed journals.

Computer Services*:* Support for Technical Assistance is requested to maintain the local computational infrastructure we will be using in this research (38 hours per year at $81, $84, $86 hourly rate). WHOI's policy is for hardware repairs, upgrades, and maintenance of computer systems to be charged at a flat hourly rate for technical assistance plus the cost of parts.

Other Costs*:* Nutrient samples will be run at the WHOI Nutrient Analytical Facility. We have budgeted for 864 samples per cruise, with a per sample charge of $28 in year 1 ($48,384) and $29 year 2 ($25,056) to measure a full suite of nitrate + nitrite, phosphate, silicic acid, and ammonium. Outside services for HPLC pigment analysis will be required in years 1 and 2 (240 samples per cruise, for a total of $33,600 in year 1 and $16,800 in year 2). Communication costs are requested to cover phone calls and faxes between the PIs and program manager, collaborators, and vendors. GRA tuition costs for the TBA

student in the Sosik lab is requested in each year ($26,945 year 1, $28,293 year 2, $29,708 year 3). The custom-made sample bottles for the triple oxygen isotope samples will be pumped down on the vacuum preparation lines of the Isotope Geochemistry Facility (IGF) at WHOI. Funding for the costs associated with labor and line use for pumping those sample bottles is requested ($4080 in year 1, $2100 in year 2). Funding is also requested for a one-time factory servicing, including cleaning and maintenance, of the Pfeiffer mass spectrometer used in the Equilibrator Inlet Mass Spectrometer system ($2500).

Outside services for video documentaries described in Broader Impacts (section 5 of the proposal) will be provided by Science Media (portfolio available at www.sciencemedia.nl). The firm is led by creative director Dan Brinkhuis, an award-winning producer who has worked with many scientific institutions worldwide, including the International Ocean Discovery Program (IODP/NSF) Netherlands Organization for Scientific Research (NWO), Royal Netherlands Institute for Sea Research (NIOZ), Woods Hole Oceanographic Institution, University of California, Utrecht University, Consortium for Ocean Leadership, NTR SchoolTV (public broadcasting), and Scientific Committee on Oceanic Research (SCOR). In short, the plan is to capture the highlights of the cruises on HD video by a professional videographer. The videographer will follow the proceedings, connect with the key science staff (interviews) and tell the science story while this science project is in progress and new insights are gained by making a suit of short videos (approximately 10 min. each) on three specific themes and one final overarching documentary (20 min) after the field research phase:

1 Interdisciplinary science of a highly productive frontal region: physics, chemistry, biology.
2 Use of OOI assets together with shipboard observations for adaptive sampling.
3 Impact of what is learned on stewardship of living marine resources, with specific connection to the fishing community.
4 Summary of the projects highlights & scientific conclusions.

The aim with this video series is also to inspire (layman) audiences and students to ‘feel’ the excitement of (multi-disciplinary) marine research and its ‘curiosity’ driven team of scientists. Sharing the vision & mission and how they operate and cooperate to get results, embrace difficulties (and cope with failures) is a very interesting cinematic and dramatic viewpoint. Filming: on board shooting will utilize two High Definition (16:9) cameras: one main professional camera and a smaller compact GoPro HD cam as backup. The GoPro HD camera can even be rigged on marine equipment and can handle water depth of 60 meters. Both are proven and compact sets for travelling, easy to handle & have amazing professional HD imaging capabilities. Editing: on board editing platform will be Apple's (laptop) Final Cut Pro system & other design applications. This professional and high end editing system can be used for all suggested videos. Other benefits: easy transfer for creating Internet clips, photographic material can be incorporated and exported to all kind of resolutions/formats. All rights to the content will be owned by WHOI. If WHOI were to resell the content, a fee to ScienceMedia would be incurred. Science Media’s plan for this project is described in the following letter with a total budget of $49,852 ($25,130 year 1, $13,308 year 2, $11,414 year 3).

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