**Collaborative Research: Developing a profiling glider PH sensor for high resolution coastal ocean acidification monitoring**

Funding Agency: NSF

Partners: Teledyne Webb, Waterlabd

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Project Summary

Ocean acidification (OA) has significant scientific and societal ramifications including the alteration of ocean biogeochemistry, ecological consequences associated with altered ecosystems, and economic losses due to the decreased survival of commercially important organisms. Yet few time series and high resolution spatial and temporal measurements exist to track the existence and movement of low pH and low carbonate saturation (Ω) water, specifically in coastal regions where finfish, lobster, and wild stocks of shellfish are located. Past ocean acidification monitoring efforts (surface buoys with pH or *p*CO2 sensors, flow-through *p*CO2 systems utilized by research vessels, water column sampling during large field campaigns) have either low spatial resolution (mooring) or high cost and low temporal and spatial resolution (research cruises). Therefore, there is a critical need to deploy new, cost-effective technologies that can routinely provide high resolution water column OA data on regional scales in our coastal ocean. Autonomous underwater profiling gliders have proven to be a robust technology that fulfills this role. A variety of sensors have successfully been mounted on Slocum gliders; however, no direct measurements of ocean pH have been collected by pH sensors mounted on these gliders. The PIs propose to: 1) modify and integrate a deep rated version of the Ion Sensitive Field Effect Transistor (ISFET)-based pH sensor, the Deep-Sea DuraFET pH sensor system, into a Slocum glider; 2) test the new sensor suite via three glider deployments to provide a rigorous “groundtruthing”; 3) deliver the OA data in real-time; and 4) examine pH/Ω dynamics on the commercially important U.S. Northeast Shelf. The proposed testing in 2018 will benefit with rigorous groundtruthing via coordination of the high resolution glider mapping of pH and Ω side-by-side with Cai’s NOAA OAP’s (Ocean Acidification Program) planned ECOA (East Coast Ocean Acidification) cruise II where a full suite of carbonate parameters (pCO2; pH; dissolved inorganic carbon, DIC; total alkalinity, TA; and oxygen, O2) will be measured either underway or on board ship.

***Intellectual Merit***: The proposal will develop the integrated glider platform and sensor system for sampling pH and possibly Ω in the water column of the coastal ocean on a regional scale. The integration of simultaneous measurements from multiple sensors on one glider will allow one to distinguish interactions between the physics (temperature), chemistry (dissolved O2, salinity-based TA, and temperature-, salinity-, and O2-based DIC, Ω), and biology (fluorescence, backscatter) of the ecosystem. High spatial and temporal resolution *in situ* pH measurements and Ω estimations will be provided in habitats of commercially important fisheries in the U.S. Northeast Shelf where ocean pH/Ω information is most critically needed. Being able to monitor pH throughout the water column is critical in order to track the movement of low pH/Ω water, understand the variability of pH/Ω, and predict how mixing events and circulation will impact pH/Ω across the shelf. This capability will allow the PIs and others to identify habitats that are susceptible to periods of low pH/Ω and/or high temporal pH/Ω variability.

***Broader Impacts****:* This project will result in a new commercially available glider pH sensor suite that will provide the foundation of what could become a real-time national coastal OA monitoring network with the capability of serving a wide range of users including academic and government scientists, monitoring programs including those conducted by OOI, IOOS, NOAA and EPA, water quality managers, and commercial fishing companies. The data produced from this new technology will allow the community to identify high-risk regions and populations of commercially important species that are more prone to periods of reduced pH/Ω and ultimately will enable us to better manage essential habitats in the future, more acidic oceans. The open accessible, automated real-time data through RUCOOL (Rutgers University Center for Ocean Observing Leadership), MARACOOS (Mid-Atlantic Regional Association Coastal Ocean Observing System), and THREDDS (Thematic Real-time Environmental Data Distribution System) would provide a warning system that would assist scientists studying ecological processes, water quality managers and conservationists to monitor impacts, and commercial operators to implement adaptive strategies. Finally, data resulting from this newly developed technology and future applications can help build and improve ecosystem models, specifically the development of coastal forecast models with the capability to predict the variability and trajectory of the low pH water. This project will also provide support for two early career researchers, two graduate students, and two undergraduate students.

# RESEARCH MOTIVATION

**Statement of the Problem**

Ocean acidification (OA) has presented great research challenges and has significant societal ramifications that range from economic losses due to the decreased survival of commercially important organisms to the ecological consequences associated with altered ecosystems (Cooley et al. 2009, Doney 2010). Particular areas of the coastal ocean are more susceptible to sustained, large increases in CO2, including those in upwelling zones (Feely et al. 2008, 2010a), bays (Thomsen et al. 2010), and areas with high riverine and/or eutrophication influence (Salisbury et al. 2008, Cai et al. 2011). Yet few time series exist to track upwelling and movement of low pH water.

Past CO2 and ocean acidification monitoring efforts have been limited to surface buoys with *p*CO2 and/or pH sensors, flow-through *p*CO2 systems utilized by research vessels, and water column sampling during large field campaigns (i.e., U.S. Joint Ocean Global Flux Study, Bermuda Atlantic Time Series, Hawaiian Ocean Times Series) with low spatial resolution (mooring) or with high cost and low temporal resolution (research cruises). Few of these efforts include the U.S. continental shelves, commercially important coastal regions where finfish, lobster, and wild stocks of shellfish are present (Hales et al. 2005, Feely et al. 2008, Vandemark et al. 2011, Xue et al. 2016).

The recent development of pH sensors for in situ measurements of seawater pH (Seidel et al.

2008, Martz et al. 2010) has resulted in a growing number of autonomous pH monitoring stations in the

U.S. New pH sensors that can withstand higher pressure (depth) show great value in monitoring coastal systems. A Deep-Sea DuraFET profiling pH sensor was recently developed by Monterey Bay Aquarium Research Institute (MBARI) and Honeywell and has been successful in collecting high quality data on a depth-profiling mooring (Johnson et al. 2009, Martz et al. 2010, Sea-Bird Scientific and Todd Martz, pers. comm.). This recent monitoring in the open and coastal ocean has shown that the pH varies greatly in time and space reflecting complex circulation patterns (Dore et al. 2009, Byrne et al. 2010, Hofmann et al. 2011, Yu et al. 2011, Nathan Rebuck, pers. comm.) that are likely due to the influence of low pH deep water through mixing and the intrusion of low pH fresh and/or estuarine water. Earlier, an innovative approach of combined *in situ* pumping and shipboard measurements of *p*CO2 also demonstrated rapid spatial variations of the CO2 system in the upwelling margin offshore Oregon, USA (Hales et al. 2005). These fluctuations may lead to large ecological and economic impacts, thus reinforcing the need for reliable high resolution monitoring of the full water column.

Significant improvements could be immediately achieved if there was a real-time monitoring network that quantified the spatial location, duration, and transport of the low pH water in coastal regions (Johnson et al. 2009, Feely et al. 2010b). The spatial, temporal, and depth resolution achieved from Slocum Webb glider data far exceeds that from traditional sampling from ships and moorings (Rudnick et al. 2004, Schofield et al. 2007). Recent calls for an international observational network for ocean acidification from Johnson et al. (2009) and Feely et al. (2010b) identified underwater gliders as a potential pH monitoring instrument that “could resolve shorter space-time scale variability of the upper ocean”. A variety of sensors have successfully been mounted on Slocum gliders. To date however, no direct measurements of ocean pH have been collected by pH sensors mounted on these gliders.

We propose to modify and integrate a Deep-Sea DuraFET profiling pH sensor into a Slocum glider. The pH sensor will be complemented with the existing glider sensors that provide physical (temperature), chemical (oxygen, salinity) and biological (fluorescence, backscatter) data. This glider sensor suite will be tested via deployments in the Mid-Atlantic Bight (MAB), a highly productive wide and shallow continental shelf that undergoes seasonal upwelling events and is influenced by oceanic, riverine and estuarine inputs. Although the MAB is embedded in the U.S. Northeast Shelf (NES), one of the nation’s most economically valuable fishing regions, water column pH measurements are sorely lacking.

This project will result in a new commercially available glider sensor suite for the planned national glider network (Baltes et al. 2014, Schofield et al. 2015, Rudnick 2016) with the application to:

1) Provide high resolution measurements of pH in coastal regions in the U.S. in real-time; 2) Determine natural variability that will provide a framework to better study organism response and design more realistic experiments; and 3) Identify and monitor high-risk areas that are more prone to periods of reduced pH and/or high pH variability to enable better management of essential habitats in future, more acidic oceans.

# Background

*Ocean Acidification*. Human activities have driven a rapid increase in atmospheric carbon dioxide (CO2), from preindustrial levels of 280 ppmv (parts per million volume) to current levels of over 400 ppmv. Current CO2 concentrations are projected to double by the end of the 21st century (Houghton et al.

1996, Solomon et al. 2007). Nearly one third of emitted anthropogenic CO2 is absorbed by the oceans (Sabine et al. 2004, Sabine and Feely 2007), resulting in reductions in seawater pH and alterations in carbonate chemistry. The reductions in carbonate ion concentration, [CO32-], largely determines the carbonate mineral stability as is defined in the aragonite saturation state, arag = [CO32-][ Ca2+]/Ksp-arag as [Ca2+] is nearly constant in seawater and the solubility constant, Ksp-arag = ([CO32-][ Ca2+])equilibrium, changes only slightly with pressure in the upper ocean. In other words when arag [CO32-]/[CO32-] equilibrium < 1, mineral dissolution is favored. The current rapid rate of oceanic CO2 uptake, at one million metric tons of CO2 per hour (Brewer 2009), is paralleled by rates of acidification at least ten times faster than any change seen in the fossil record over the past 65 million years (Ridgwell and Schmidt 2010). These rapid changes are expected to cause adverse effects, propagating from individual species of both calcifying and

non-calcifying marine organisms to entire ecosystems (Riebesell 2004, Raven et al. 2005, Fabry et al. 2008, Doney et al. 2009). There is a critical need for observing ocean acidification in our coastal ocean. While these monitoring efforts are beginning to expand nationally, they are still severely limited in temporal and spatial resolution and severely lacking in several economically and ecologically important regions, including the U.S. NES.

*Overcoming pH sensor challenges*. As there is no widely accepted method yet to measure [CO32-]

directly, it is calculated from two of the four commonly measured parameters (pH, *p*CO2, dissolved inorganic carbon [DIC] and total alkalinity [TA]) with known thermodynamic constants. So far for *in situ* monitoring, *p*CO2 is the only popular and reliably used sensor with recent addition of pH as DIC and TA analysis involves balky and time-consuming instruments (see Wang et al. 2013). The measurement of pH appears very simple but has always been a challenge for the ocean science community (Dickson 1993).

Past automated monitoring efforts have been limited to surface measurements, and water column profiles were only possible via manual sampling from a ship. However, recent pH sensors have been demonstrated to be rapid responding and stable despite large gradients in pressure, temperature, and chemistry in which the sensors must operate. The Honeywell DuraFET Ion Sensitive Field Effect Transistor (ISFET) packaged in a durable Ryton® body has a rapid response time (1 sample every 3 seconds; 10 times faster than glass electrodes), is capable of long-term accuracy of 0.03 or better pH units (Bresnahan et al. 2014), and is stable and precise for long-term *in situ* pH measurements (within 0.005 pH units on a scale of weeks to months; Johnson et al. 2009, Martz et al. 2010, Todd Martz pers. comm.). A commercially available version of the DuraFET, the Satlantic SeaFET, is rated to operate to a depth of around 70 meters; however, the SeaFET is not ideal for profiling due to pressure hysteresis (Todd Martz, pers. comm.). A deep rated version of the FET-based pH sensor, the Deep-Sea DuraFET pH sensor system, was recently developed via coordinated efforts between Sea-Bird, Monterey Bay Aquarium Research Institute (MBARI), Scripps Institution of Oceanography, and Honeywell. It is capable of water- column profile sampling from the surface to 2000m, is currently in the later phases of testing, and is being adapted by Sea-Bird Scientific for commercial use on profiling floats. This sensor has been adapted for stable sampling under pressure and temperature changes via pressure protected packaging and a pressure

tolerant reference electrode. This model, which was tested on a Teledyne Webb Research Apex profiling float and several CTD casts in the field, delivered long-term (months) high quality pH data (precision of

* 1. pH units and a stability of 0.005 pH units over long sampling periods) and retained a calibration traceable to certified reference materials (Sea-Bird Scientific, pers. comm.).

*Need for high resolution depth-profiling sensors*. While surface water mapping of pH can be valuable, episodes of low surface pH are typically driven by mixing events where low pH water either upwells to the surface from below the thermocline or flows onto the shelf via rivers and bays. Being able to monitor pH throughout the water column is critical in order to track the movement of low pH water, understand the variability of pH, and predict how mixing events and circulation will impact pH across the shelf. While ships can provide detailed water column profile data, their costly operation limits both temporal and spatial coverage. Moorings can collect high resolution temporal data, but cannot resolve spatial variability. Therefore, there is a critical need to deploy new, cost-effective technologies that can routinely provide high resolution data on regional scales in our coastal ocean. Autonomous underwater gliders have proven to be a robust technology that fulfills this role (Rudnick et al. 2004, Schofield et al.

2007).

*Gliders as a tool for high resolution sampling*. Coastal underwater gliders are buoyancy driven robotic systems thus allowing batteries to power at sea missions for months at a time. They are capable of collecting data in highly variable currents over water depths of 10 to 1000 meters allowing them to sample from the nearshore coastal ocean to the deep sea. The Slocum Glider, produced by Teledyne Webb Research, is the genesis of all present ocean gliders. They have demonstrated their operational maturity by collecting data over sustained periods of time over the last 10 years (Schofield et al. 2013) and as such are chosen as a key tool for the United States Navy under the Littoral Battle Space - Glider program (LBS-G), NOAA under the Integrated Ocean Observing System (IOOS), NSF under the Ocean Observatories Initiative (OOI), as well as numerous academic institutions and international partners.

These 1.5 meter autonomous underwater vehicles profile the water column in a sawtooth pattern by shifting small amounts of ballast to dive and climb at vertical speeds of ~20 cm s-1 resulting in high data density and full water column coverage. At surfacing iridium satellite communications enable real-time

data transfer.

The latest generation of Slocum glider, the G2, includes enhancements to facilitate multiple sorties with a single glider platform, modular buoyancy engines, optional power sources, and a shock and vibration tolerant construction. Proportional buoyancy control provides the capability for a neutral buoyant mode and deep water sub-surface inflections. The G2 accommodates a modular center section payload bay, providing a flexible system for integrating new sensors. These nominal 7 liter center sections are made of a 6061-T6 aluminum hull to facilitate flexible machining to readily accommodate ported windows into the dry side of the vehicle, and have been modified for physical, optical, and acoustic payloads. This design allows for dedicated sensor payload bays that can be readily adapted or exchanged, as needed for each mission objective. In addition, the ported windows allow for individual sensor swapping or replacement. The dedicated science-bay motherboard contains a Persistor CF-1, which is responsible only for data-logging and parsing. This additional board provides a more reliable and higher rate of sampling since it unloads the main glider CPU of these tasks. The motherboard allows connection of up to 7 sensors with 7+ switched power lines. An internal development project, already completed, was to upgrade the existing science-bay motherboard. The new design uses the identical Persistor module, duplicated serial expansion circuitry, and an off-the-shelf DC-DC converter. Additional switched power lines and connectors have been added to support increased sensor capacity. Both Alkaline and Lithium primary batteries are available for use on the glider as an energy source. The configuration for lithium is 78 DD cells in a 3 series. To enhance energy conservation, low power mode vehicle software has been modified to not only turn off science sensors when not used but also the science processor itself. These developments provide a significant endurance gain, which this program will benefit from.

The modular hardware and software design facilitates missions with all required sensor packages.

Satellite communication through Iridium and Argos allows the glider trajectory to be adjusted during missions based on real-time data to adaptively optimize sampling to best map features of interest. Glider deployments are also cost-effective. Costs of the glider ($998 day-1) are only 4% and 66% of the daily cost of operating research class vessels and smaller coastal vessels, respectively (Schofield et al. 2010).

*Glider national network*. Glider operations are coordinated through the global Iridium communication network and many gliders can be deployed simultaneously to provide a distributed ocean sampling network. Regional glider networks already exist and have proven valuable in providing baseline ocean observations to address such issues as natural climate variability and water quality (Schofield et al. 2010, Zaba and Rudnick 2016). Due to the growing national and international community of glider operators, there is an increased focus to develop a national glider network (Baltes et al. 2014, Schofield et al. 2015, Rudnick 2016). A national glider network is essential to connect the coastal and global ocean.

Ocean acidification is a growing global issue; thus, the development of a glider pH sensor suite will be of utmost scientific, economic and ecological value.

*Location of instrument testing*. The MAB is the continental shelf region that extends between Cape Hatteras, NC to Nantucket Shoals-Georges Bank off Massachusetts. The region encompasses 10 states, the District of Columbia, 107 congressional districts and ~78M people (25% of US population). The nation’s highest coastal population density makes increasingly competing demands for marine and coastal resources. The U.S. NES is one of the most productive large marine ecosystems (LME) in the world (O’ Reilly and Zetlin 1998, Sherman et al. 2002) and supports diverse and abundant fin, lobster, and shellfish populations (Gates 2009), a major marine resource and a critical component of the United States economy (Sherman et al. 1996).

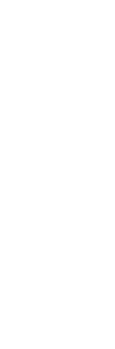
The MAB includes five major estuarine systems and a broad shelf that extends out several hundred kilometers cut by multiple shelf-break canyons and bounded offshore by the shelf-break front. The Southern New England shelf break is on the northern edge of the MAB. It connects the MAB shelf with the highly productive Georges Bank (Zhang et al. 2013), which supports historically lucrative fisheries for groundfish, lobster, and shellfish. It is influenced by a combination of wind forcing in the MAB and the Shelf Break-Jet that runs west along the shelf break and is sourced by the Labrador current that goes through the Gulf of Maine and around Georges Bank. Upwelling occurs in this region Spring- Summer and can support high productivity (Zhang et al. 2013). Previous investigations in this region have demonstrated that physical processes here are highly dynamic and variable, and are still not well understood (summarized in Zhang et al. 2013). Thus, it is the chosen study site of the OOI Pioneer Array. Nutrients are supplied to the Georges Bank region by inflows of interior Gulf of Maine waters, which are brought onto the Bank by tidal pumping on the Northern Flank (Townsend et al. 2014). The deep Northeast Channel in the Gulf of Maine connects the shelf to off-shelf waters and is thus the major throughway by which deep water enters the ecosystem (Townsend et al. 2006). As cold, fresh, poorly buffered Gulf of Maine waters have reduced pH (Wang et al. 2013), it is likely that low pH water flows over these deep groundfish and shellfish beds on Georges Bank.

The waters on the MAB exhibit considerable seasonal and interannual variability in temperature and salinity (Mountain and Taylor 1998). In late spring and early summer, a strong thermocline develops at about the 20 m depth across the entire shelf, isolating a continuous mid-shelf “Cold Pool” of water that extends from Georges Bank to Cape Hatteras (Houghton et al. 1982) and has been linked to the distribution and recruitment of commercially important fin and shellfish species (Goldberg and Walsker 1990, Steves et al. 2000, Sullivan et al. 2000, Sullivan et al. 2005, Weinberg 2005). The Cold Pool is a

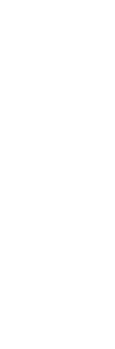
distinctive mass of cold (< 8o C) bottom water, originating in the Labrador Sea and fed into the MAB

from the Scotian Shelf and Gulf of Maine, that is cut off from the surface via surface warming during the summer. This summer stratification forms one of the most extreme coastal thermoclines on Earth with temperatures ranging from 30º to 8º C with an extremely sharp thermocline that spans a 20° gradient in 2- 3 meters (Biscaye et al. 1994).

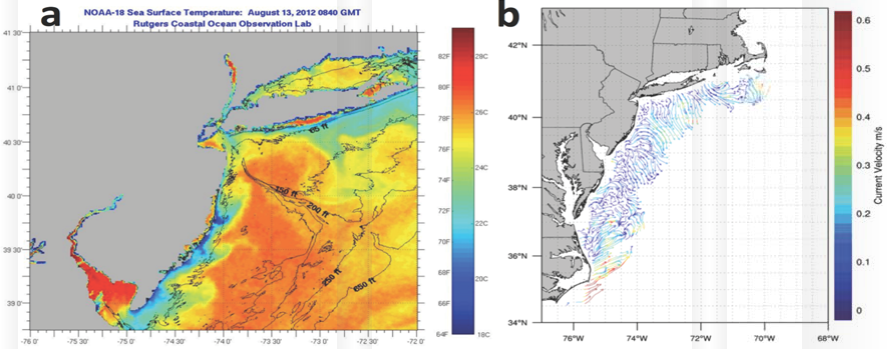










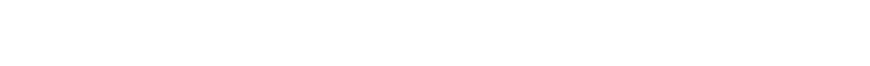


**Figure 1**. Upwelling of Cold Pool water in the MAB in August 2012. a) Sea Surface Temperature showing upwelling of Cold Pool water near the coast; b) Hourly surface current field (5 MHz) showing offshore surface flow.

Upwelling occurs annually each summer in the MAB. It is driven by SW winds associated with the Bermuda High (Glenn and Schofield 2003, Glenn et al. 2004), and then Ekman forcing brings Cold Pool water forced to the surface layers (Glenn et al. 2004; Fig. 1). The most intense upwelling (size and duration) occurs in summers following colder than usual falls and winters perhaps reflecting the spatial

extent of the MAB Cold Pool (Glenn et al. 2004). Strong correlations between southerly winds and rapid decreases in surf zone temperatures of up to 8-9o C over 2-3 days have been attributed to upwelling that shifts the MAB Cold Pool toward the coast (Hicks and Miller 1980; Fig. 1). The total number of

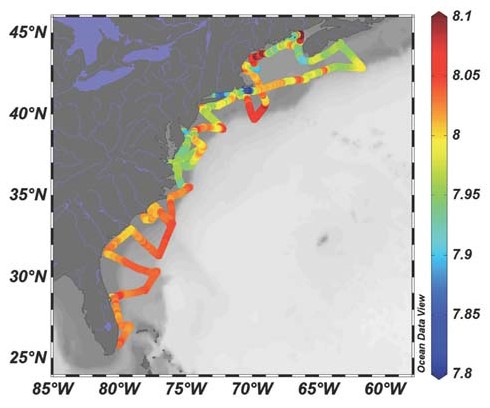
upwelling days per summer season range from 20 to 66 with an average of 37 upwelling days each summer and an average upwelling event lifetime of one week (Glenn et al. 2004). Off the coast of NJ, upwelled water that initially occurs uniformly along the coast is concentrated into an alongshore line of recurrent upwelling eddies that are associated with the underlying topography (Song et al. 2001) and co-located with historical regions of high primary productivity and fishing activity (Church et al. 1994, Wood et al. 1996) and low dissolved oxygen.











**Figure 2**. Map of surface pH (calibrated against spec-pH and in pHT scale) along a ship transect during the ECOA I cruise 19 June-25 July 2015 (Cai, unpublished data). Here underway pH was measured by a DuraFET pH sensor housed in a flow-through cell. On board, pH was also measured spectrophotometrically with purified pH dye, which was used to calibrate and evaluate the DuraFET pH. Two previous cruises (Gulf of Mexico and East Coast Carbon Cycle, GOMECC I and II) were conducted in summer 2007 and 2012. A similar survey is scheduled for summer 2018.

Cai is co-PI with Joe Salisbury of UNH on this project.

*Contrasting carbonate chemistry*. Sampling for water chemistry parameters in the surface waters of the U.S. NES has been conducted since 1973 with occasional measurements of carbonate chemistry (for

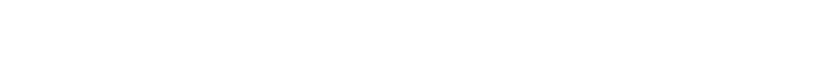
example the 1996 DOE Ocean Margin

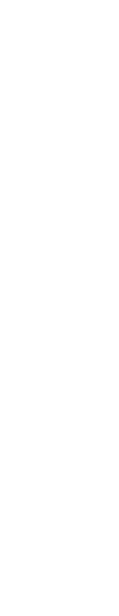
Program and recent NOAA Ocean Acidification Program [NOAA OAP] cruises). One recently NOAA OAP-funded East Coast OA (ECOA I) cruise was dedicated to these measurements (Fig. 2). These surveys depict large natural spatial and seasonal variability and possible decadal

changes of surface carbonate chemistry on the U.S. NES (Fig. 2 and Cai unpublished). The underlying mechanisms causing this variability are unresolved but likely including upwelling of the Cold Pool water, freshwater from the Labrador Current and the large estuaries, air-water gas exchange, and biological processes. Surface sampling from this region suggests that due to their relatively low pH, aragonite saturation, and buffer intensity, waters of the U.S. NES may be more susceptible to acidification pressures than southern locations (Wang et al. 2013). Surprisingly, possible increase in surface water arag in the MAB is also reported between 2012 and 2007 (Wanninkhof et al. 2015) and 2015 and 2007 (Cai unpublished).

We have very little information on how the Cold Pool, and upwelling events, regulate pH variability on the NES. Our recent survey reveals the existence of large scale low pH and arag water in the MAB and this near sea surface acidification correlates well to the strength of the Cold Pool (see Fig. 3). The gradients of pH and arag are particularly sharp, posting great challenge to conventional methods in characterizing these critical zones. As hypothesized, Cold Pool water exhibits lower pH and aragonite saturation. This likely impacts pelagic and benthic organisms (finfish, groundfish, lobster, shellfish) on the shelf and will create episodic low pH events throughout the water column consistent with other upwelling regions that have high variability in

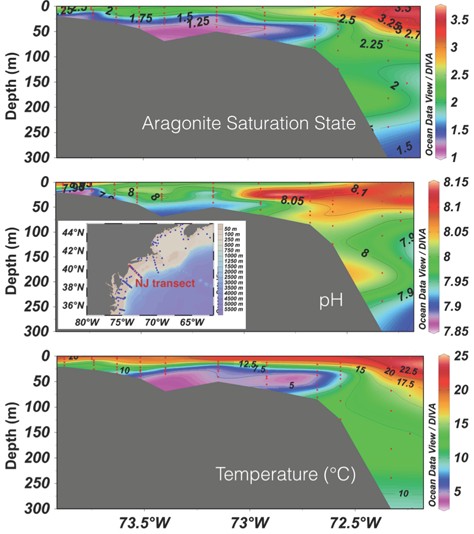
pH (reviewed in Hofmann et al. 2011, Yu et al. 2011) where deep, corrosive (low pH) water is upwelled to the surface (Feely et al. 2008, Feely et al. 2010a). Atlantic shellfish exhibited lower survivorship, delayed development, and shell dissolution after only days of exposure to sediments just slightly more acidic than average conditions (Green et al. 2009, Talmage and Gobler 2009). The proposed glider pH approach will greatly advance our ability to understand this important process of coastal water pH control mechanism.











**Figure 3**. Vertical sections of (top) aragonite saturation, (middle) pH, and (bottom) *p*CO2 from a cross-shelf transect in New Jersey in the Middle Atlantic Bight (MAB). Data was collected during the ECOA I cruise (June/July 2015). Here arag and pH are calculated from measured DIC and TA (further data assessment and synthesis are underway).

Monitoring and characterizing pH along with temperature is also important as shellfish and other taxa, become more sensitive to OA when they are in warmer water (synthesized in Kroeker et al. 2013). This is especially important in our test site, which is warming 2-3x faster than the global average (Wu et al. 2012, Forsyth et al. 2015, Zhang and Gawarkiewicz 2015) and is predicted to continue accelerated warming (Saba et al.

2015). While there is, for the most part, high resolution temperature data in regions where shellfish and lobsters are abundant, we critically lack spatial and temporal maps of pH, *p*CO2, and calcium carbonate saturation states in these regions.

# RESEARCH GOALS, OBJECTIVES, AND HYPOTHESES

* + 1. Develop and integrate a Deep-Sea DuraFET profiling pH sensor into a glider and conduct laboratory testing and calibration (DuraFET, CTD, BB2FL ECO puck, Aanderaa optode) (Yr 1)

*Rutgers (Saba, Miles) will collaborate closely with subcontracts Sea-Bird Scientific and Teledyne Webb Research for sensor development, integration, and testing. All sensors will be factory calibrated. We will conduct in situ calibrations of the CTD, ECO puck, and Aanderaa optode. We will collect bottle samples next to the glider at multiple depths for analysis in the UD (Cai) laboratory for carbonate chemistry parameters (pH, TA, and DIC) for cross calibration of the Deep-Sea DuraFET profiling pH sensor. UD (Cai) will use sample based data collected here as well extensive data collected during NOAA’s GOEMCC I (2007), GOMECECC II (2012), and ECOA I (2015) and historical data to develop a robust salinity-based TA model (to be improved once ECOA II (2018) data are available in year 3). Cai will also examine the relationship between DIC and S, T, and O2 and develop a DIC predictive model to compare with the calculated DIC from glide- based measurement of pH and TA.*

* + 1. Conduct two glider/pH sensor suite test deployments (cross-shelf transects off the coast of NJ) and one 60-day deployment (from Georges Bank to Tuckerton) (Yr 2)

*The test deployments will be conducted via small vessels. The 60-day glider flight will be deployed during the ECOA II summer 2018 research cruise at no cost to this proposal. As high precision carbonate parameters (underway DuraFET pH and pCO2, spec-based discrete pH, DIC and TA will all be measured on board ship by UD and NOAA-AOML laboratories, this coordination will allow for in-depth evaluation and groundtruthing of the glider pH sensor suite. We will receive technical support from Sea-Bird Scientific and Teledyne Webb Research for the duration of this project.*

* + 1. Make real-time glider data available through RUCOOL (Rutgers University Center for Ocean Observing Leadership), MARACOOS (Mid-Atlantic Regional Association Coastal Ocean Observing System), and THREDDS (Thematic Real-time Environmental Data Distribution System).

*Sea-Bird Scientific and Teledyne Webb Research will develop software that will allow the integration of temperature and salinity data from the glider CTD with raw voltage data from the Deep-Sea DuraFET to calculate pH. This data can then be transmitted via Iridium in real-time. The Rutgers’ software technician, after establishing real-time quality control procedures, will make the data from all the glider sensors publicly available in real-time. Finally pH data after calibration against the spec-based and shipboard sensor-based pH will also be archived within one year of collection.*

* + 1. Characterize water column pH dynamics along the glider transects (Yr 3)

*We hypothesize:*

*H1: Water with lower pH will be associated with Cold Pool water off the NJ shelf and in Southern New England or with colder, fresher water flowing from the Gulf of Maine over Georges Bank while pH in area affected by river plume is relatively high due to high biological production.*

*H2: Seawater pH will be reduced throughout the water column during upwelling events on the shelf. While upwelling also leads to high biological production, simultaneous warming and slow air-sea CO2 exchange keep the upwelled water at relatively low pH and high pCO2.*

*We will also identify habitats that are susceptible to periods of low pH and/or high*

*temporal pH variability (i.e., near a) historically abundant lobster fishing grounds in Southern New England; b) scallop, quahog, and clam beds in New Jersey shelf waters of the Mid-Atlantic Bight; and c) lobster, groundfish, and deep shellfish beds in Georges Bank)*.

# PLAN OF WORK

**Develop and integrate the Deep-Sea DuraFET profiling pH sensor into an underwater glider**

*Integration*. The Deep-Sea DuraFET pH sensor will be modified by Sea-Bird Scientific, and its integration into a Slocum glider will be a coordinated effort between Rutgers, Sea-Bird Scientific, and Teledyne Webb Research. Sea-Bird Scientific, which includes the set of Sea-Bird Electronics, WET Labs, and Satlantic, companies, draws on decades of collective sensor development / engineering expertise to provide superior oceanographic and water quality instruments to enable the advancement of science, technology and environmental monitoring worldwide. The Sea-Bird Scientific group of companies has extensive sensor engineering and calibration expertise, and is known worldwide for their oceanographic instrumentation. This includes conductivity, temperature, pressure sensors, dissolved oxygen sensors, and pH sensors. Currently, Satlantic manufactures a DuraFET based *in situ* sensor, called SeaFET. They have a successful history of working with academic partners to integrate their sensors into durable ocean monitoring systems. Most notably, Sea-Bird Scientific, along with MBARI, Scripps Institution of Oceanography, and Honeywell, are recent winners of the 2nd place award in the Wendy Schmidt Ocean Health X-Prize pH challenge for the development of the Deep-Sea DuraFET pH sensor system. It is currently in the process of being commercialized by Sea-Bird Scientific. Teledyne Webb Research, a Business Unit of Teledyne Instruments, Inc., has been dedicated to the design, production, service, and data reliability of underwater autonomous gliders and Apex floats for the past 28 years. They maintain rigorous, dedicated production, quality assurance, quality control, testing, and customer service teams.

Drs. Saba and Miles are two of the five faculty members in the Rutgers University Center for Ocean Observing Leadership (RUCOOL), which has a long history of collaboration with Teledyne Webb Research and Sea-Bird Scientific and will ensure a competent integration path to success for this proposed project. We manage a fleet of 20+ Slocum gliders, a diverse collection of sensors for glider payload bays, and a staff dedicated to glider piloting and delivering real-time glider data. We have extensive experience with glider sensor calibrations and data QA/QC and analysis.

The modifications to the Deep-Sea DuraFET proposed here include a size-reduced remote head and into a custom glider payload bay (Fig. 4).

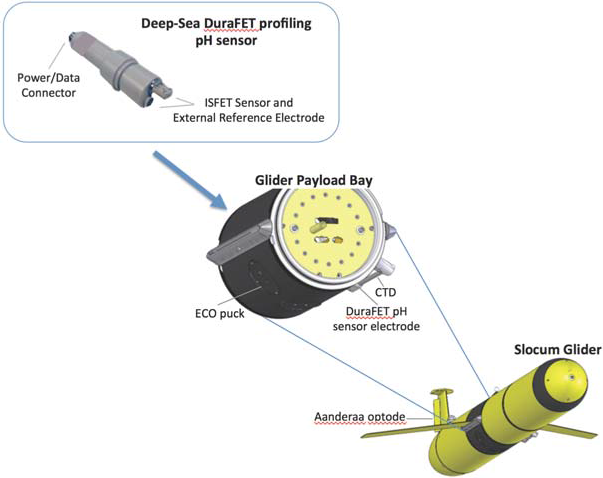












**Figure 4**. Integration of the Deep-Sea DuraFET profiling pH sensor into a Slocum Glider.

Given the light sensitivity of the Deep-Sea DuraFET and desire to be closely coupled with CTD data acquisition, the Deep-Sea DuraFET will be reconfigured by Sea-Bird Scientific to fit into the existing rectangular glider CTD port utilizing a pumped system to pull seawater in past both the pH and CTD sensor elements.

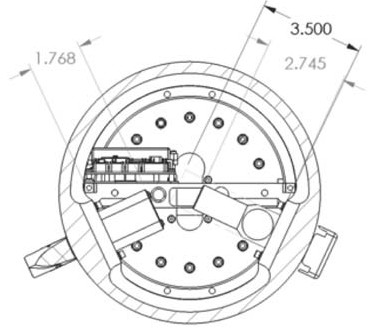
Teledyne Webb Research will facilitate integrating this resulting package into a standard 2 ECO port hull section.

Depending on spatial constraints in the final design, Teledyne Webb Research will work with

Sea-Bird Scientific and, if required, flip the payload bay to increase the available sensor can depth into

the vehicle from the existing 1.77" to 2.75" or up to a maximum of 3.50" (Fig. 5). Additionally, Teledyne Webb Research will provide any necessary chassis, wiring, and firmware modifications. This standalone science bay will also be outfitted with an existing sensor provided by Rutgers (i.e., WET Labs ECO puck). It is planned for the resulting sensor to fit into a





**Figure 5**. Potential modification to payload bay sensor can depth to accommodate the Deep-Sea DuraFET.

standard ECO puck opening, common to many existing Slocum gliders. Additional sensors on the same glider will include a factory calibrated CTD and a WET Labs BB2FL ECO puck configured for simultaneous fluorescence, CDOM, and optical backscatter measurements. An existing Aanderaa optode for measuring dissolved oxygen will also be integrated into the glider. Examining the interaction of water with low pH and reduced dissolved oxygen in upwelling regions is important as this will result in water with lower pH and lower saturation state which could magnify biological impacts (Feely et al. 2010a, Cai et al. 2011). Teledyne Webb Research will environmentally cycle (pressure and temperature), bench test, and perform in- water test flights on the completed assembly. Factory support will be provided during Rutgers deployments.

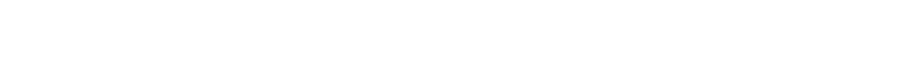
The ultimate goal is to produce a readily upgradeable, commercialized pH sensor system for many existing Slocum gliders.

# Proposed glider flights

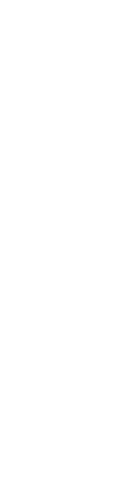
After integrating the Deep-Sea DuraFET into a glider, we will then demonstrate and evaluate its capability on the MAB shelf. The Deep-Sea DuraFET profiling pH sensor is currently being tested to 2000 m; however, most of our sampling will be in shallow shelf water (< 200 m). We propose two test deployments in spring 2018 that will repeat the NJ cross-shelf transect completed during the summer 2015 ECOA I research cruise (Fig. 3). Due to the short deployment time (2-3 weeks each), the gliders will be fitted with an alkaline battery pack. These test deployments will allow for initial testing and water sampling for *in situ* calibration of the glider/pH sensor suite (see below). Rutgers and the University of Delaware will work closely with Sea-Bird Scientific and Teledyne Webb Research to address any problems that arise during the laboratory testing and field test deployments. Hardware complications will require the payload bay to be returned to Teledyne Webb Research to interface with both Teledyne and Sea-Bird engineers for troubleshooting and further modification if needed. We will also work with them to develop or update software or firmware for any issues with data integration and output.

Once testing is complete, we will deploy the glider/pH sensor suite on Georges Bank during its ECOA II cruise during summer 2018, during which samples will be collected throughout the full water column and analyzed for carbonate chemistry parameters at sea by Cai and Wanninkhof’s groups. The glider will be deployed from the ECOA II cruise near Georges Bank and run several cross-shelf zig zags (all within 200km of the coastline) southward on the shelf that will complement the cruise transect (cruise transect: Fig. 2; proposed glider transect: Fig. 6). We will recover the glider off the coast of Tuckerton, NJ, via a small vessel for a total transect distance of about 1200 km. About halfway through the transect (near Long Island Sound), we will use a small vessel to briefly recover, clean the glider to remove fouling, and re-deploy in order to prevent ballasting issues from biofouling. From extensive experience of RUCOOL deploying gliders in the MAB, we estimate a daily distance of 20 km and thus a 60-day deployment for the entire proposed transect.

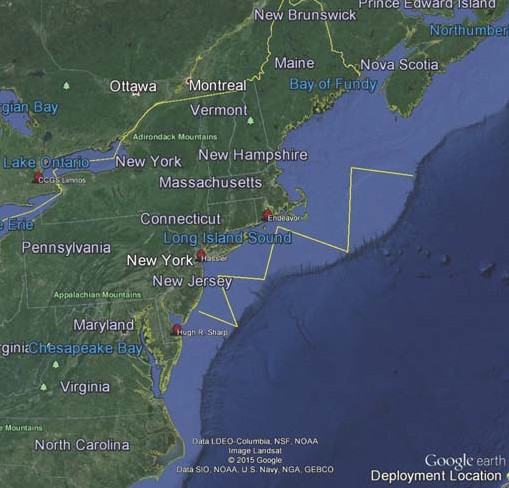
The glider ultimately moves more slowly than the planned research cruise. While the glider transect from Georges Bank to Tuckerton, NJ (Fig. 6) will take about 60 days, the ECOA II vessel will finish its entire transect from the Scotian Shelf to South Florida (Fig. 2) in about 30 days. We estimate the glider and the ECOA II vessel will be in close proximity for about 10 days in the northern MAB, during which time we will focus on groundtruthing the glider pH data (see details below).











**Figure 6**. Map of the U.S. Northeast shelf depicting the proposed transect for the 60-day glider deployment from Georges Bank in the north to Tuckerton, NJ (yellow line).

There will then be a lag in time between glider data and water column profiles from the ECOA II for the remainder of the glider deployment; however because the glider path will be programmed to follow the cross-shelf transects of the ECOA II research cruise track from Georges Bank to Tuckerton, NJ, we will have the advantage to observe changes in pH over time.

The glider will be fitted with a lithium battery pack, which will provide sufficient power for the science payload for the duration of the deployment. We will benefit from the coordinated glider and ship sampling efforts to groundtruth the pH data (see below). The proposed glider transect will occur during summer when the stratification allows for direct observation of the distinct Cold Pool and when episodic upwelling events are typical on the shelf. The sampling will also occur in historically abundant lobster fishing grounds in Southern New England (SNE); 2) scallop, quahog, and clam beds in New Jersey shelf waters of the MAB; and 3) lobster and deep shellfish beds in Georges Bank (GB).

# Quality control for glider sensors

The hydrographic and oxygen data collected during our proposed glider missions will follow the QA/QC procedures outlined in an approved EPA Quality Assurance Project Plan (QAPP) that has been developed specifically for glider observations of DO along the New Jersey coast (Kohut et al. 2014). The QAPP clearly states the pre- and post-deployment steps needed to ensure the quality of the data collected during each mission (Kohut et al., 2014). The procedures include pre- and post- deployment steps for each sensor to ensure data quality for each deployment. Beyond these common measurements, the science bay of the glider will be outfitted with and ECO puck and the Deep-Sea DuraFET profiling pH sensor.

QA/QC procedures are described in detail below.

CTD*.* The hydrographic data for each mission will be sampled with either a pumped or unpumped CTD specifically engineered for these gliders. Based on manufacturer specifications, the CTD will be sent to the factory for an annual calibration. The QAPP (Kohut et al. 2014) requires a two-tier approach to verify the temperature and conductivity data from the glider CTD. The first tier test is a pre- and post- deployment verification between the glider CTD and a factory calibrated sea bird-19 CTD in our ballast tank in New Brunswick, NJ. The second tier test is an in situ verification at the deployment and recovery of the glider. For each deployment and recovery we will lower a separate CTD meeting manufacturer calibration requirements to compare to a concurrent glider profile. This second tier test gives an in situ comparison within the hydrographic conditions of the mission.

Aanderaa optode. The dissolved oxygen (DO) data will be sampled with an optical sensor unit manufactured by Aanderra Instruments called the optode. Like the CTD, we will deploy a glider optode that is calibrated by the factory at least once per year. In addition to these annual calibrations, we will also complete pre- and post- deployment verifications. To do this we will compare optode observations to concurrent Winkler titrations of a sample at both 0% and 100% saturation. Results of each comparison will be documented. The QAPP (Kohut et al. 2014) requires that all optode measurements are within 5% saturation of the results of the Winkler titrations for both the 0% and 100% saturation samples. Winkler titration of O2 on Niskin bottle samples collected *in situ* will also be performed to calibrate sensor-based DO.

BB2FL ECO puck. The puck we will deploy will undergo standard factory calibration from WET Labs (recommended every 1-2 years for pucks in gliders). Fluorescence data from the puck will be verified during testing and deployments with simultaneously collected field samples for fluorescence. If drift occurs, the puck will be swapped out with another puck (we have several on-hand at RUCOOL) and the *in situ* calibration will be repeated. Any drifting pucks will be sent back to WET Labs for maintenance and re-calibration.

Deep-Sea DuraFET profiling pH sensor. In order to optimize sensor design under variable pressure and temperature, this sensor will be tested at Sea-Bird Scientific’s high pressure test facility according to their specifications using Tris certified reference materials (CRMs) obtained from Andrew Dickson at UCSD Scripps Institution of Oceanography. We will follow Best Practices for autonomous pH measurements with the DuraFET, including the rigorous calibration procedure, recommended by Bresnahan et al. (2014) and Martz et al. (2015). We will collect water samples next to the glider in the seawater ballasting tank during laboratory testing and *in situ* from multiple depths from small vessels at each glider deployment and recovery and during the ECOA II cruise when the research ship is within close proximity to the glider. Specifically, during the ECOA II cruise, we will undergo high vertical resolution depth water sampling (average 5 to 10 meters) from the ship at roughly 73.3°W where a particularly sharp vertical pH change was observed during ECOA I (Fig. 3). Then, we will have the glider near the ship on standby ready to do profile right before, during, and after the research vessel leaves the spot. The water samples samples will be collected manually via SCUBA divers from small vessels if weather permits or via ship-board depth profiles with a CTD and Go-Flo bottles. They will be preserved and analyzed immediately upon return to the laboratory for carbonate chemistry parameters (spec-pH, total alkalinity, dissolved inorganic carbon, and DO by Cai) and used for *in situ* cross calibration of the Deep-Sea DuraFET profiling pH sensor and total alkalinity estimations. (During the ECOA II cruise, all the above parameters plus underway *p*CO2 will be measured at sea.) PI Saba recently learned this calibration process (using a SeaFET) at the recent Autonomous pH Sensor Best Practices Workshop hosted by Todd Martz and Andrew Dickson at Scripps Institute of Oceanography. This robust *in situ* calibration and groundtruthing, along with plans to check/remove biofouling during deployments, will improve the accuracy of the pH sensor (Bresnahan et al. 2014). PI Saba recently learned this calibration process (using a SeaFET) at the recent Autonomous pH Sensor Best Practices Workshop hosted by Todd Martz and Andrew Dickson at Scripps Institute of Oceanography.

While pH data alone will be extremely valuable, at least two out of the four measurable carbon parameters need to be determined to fully characterize the marine carbonate system and OA. Thus, measurements of pH by the DuraFET sensor will be complemented with estimations of total alkalinity (AT) from simultaneous temperature and salinity measurements via a CTD mounted on the glider (Cai et al. 2010; Lee et al. 2006, Johnson 2010). From Lee et al. (2006), we can use the best-fit second-order polynomial model in Zone 3 (North Atlantic) for the MAB and New England estimates. Cai et al. (2010) and Wang et al. (2013) determined that AT exhibited near-conservative behavior with respect to salinity in the Atlantic along the East coast of the US. We plan to take several samples at several depths during each glider deployment and recovery; together with ECOA II data and previous data Cai’s group have collected, this will allow for regular tuning and refinement of the alkalinity-temperature-salinity relationships that are to be used. Furthermore, deployments in three different regions on the NES will

allow us to evaluate the robustness of the alkalinity-temperature-salinity relationships across time and space. We will also analyze DIC from the ship-collected samples. This will allow an additional carbonate chemistry parameter with which to cross-check the alkalinity estimates.

Carbonate chemistry samples will be transferred from Go-Flo bottles to 300 mL borosilicate glass BOD bottles according to Dickson et al. (2007). Samples will be poisoned with 50 μl saturated mercuric chloride (HgCl2) solution immediately after sampling, and sealed with a ground glass stopper for analysis of TA and DIC in Cai’s lab. Seawater samples will also be taken for measuring dissolved O2 concentration by Winkler titration (Cai). Seawater will also be collected, filtered, frozen, and analyzed for dissolved nutrients (silicate, nitrate, phosphate) at the Rutgers laboratory. We estimate ~30 samples collected at each glider deployment and recovery, at multiple depths along the glider transect (duplicate samples at 5 depths for three glider profiles). Duplicate samples will also be collected simultaneously to determine the concentration of dissolved nutrients (nitrate, phosphate, and dissolved silicate) for inclusion into the estimation of carbonate chemistry parameters.

Discrete sample pH will be measured both spectrophotometrically using purified dye from R. Byrne (Clayton and Byrne 1993, Liu et al. 2011) and with Ross glass pH electrodes calibrated with *Tris* buffers at appropriate salinity (Millero 1986). Cai’s lab has built a spec-pH unit similar to the Dickson Lab (Carter et al. 2013) and used it during ECOA I. AT titrations will be performed using open cell Gran titration following the method detailed in Cai et al. (2010) and Huang et al. (2012). DIC will be measured using an Apollo Scitech DIC analyzer, which acidifies a small volume of seawater (0.8 mL) and quantifies the released CO2 with a LI7000 analyzer (Huang et al. 2012) during test flights or using a SOMMA during ECOA II by the Wanninkhof lab (NOAA-AOML) (Dickson et al. 2007). Discrete water sample DIC will be measured as described in Huang et al. (2012). Precision of TA and DIC are better than ±0.1%. Measurements of pH, AT, and DIC will be quality controlled using CRMs obtained from Andrew Dickson at UCSD Scripps Institute of Oceanography. Dissolved silicate will be analyzed according to Strickland and Parsons (1968) and nitrate/phosphate will be analyzed according to Grasshoff et al. (1999). Final carbonate system parameters, including Ω and *p*CO2, will be calculated from both glider data and from ship-sampled data using CO2calc software (Robbins et al. 2010) using a total pH scale (mol/kg-SW), K1 and K2 constants (Mehrbach et al. 1973) with refits (Dickson and Millero 1987), and the acidity constant of KHSO4 in seawater (Dickson 1990).

Groundtruthing pH data. The suite of carbonate chemistry parameters measured from water samples collected next to the glider from small vessels at each glider deployment and recovery and in coordination with the ECOA II cruise will allow for rigorous groundtruthing of the glider pH data.

Additionally, data provided by the OOI Pioneer Array, including pH and other carbonate chemistry parameters, will provide a thorough leveraged foundation for glider pH profiling proposed in this region for this project. This will allow us to appropriately determine response times of the Deep-Sea DuraFET glider pH sensor, how those response times vary with other parameters (temperature, salinity, depth/pressure), and allow for time lag corrections in our data software program.

# Cyberinfrastructure and Pairing pH with Habitats

We propose that the real-time automated data and graphical images of the data will be made freely available in the NetCDF file format through RUCOOL, MARACOOS, and THREDDS, addressing the needs of the diverse community (academic, Federal scientists, stakeholders/commercial fisheries, and policy makers) who require ocean pH information. In order to demonstrate ecological and economical benefits and application of our developed glider/pH sensor suite, we will test hypotheses relating pH to the Cold Pool and episodic upwelling events. We will also pair glider data with historical fisheries survey data (i.e., MAB Northeast Fisheries Science Center sea scallop, Marine Resources Monitoring, Assessment, and Prediction [MARMAP], Ecosystem Monitoring [EcoMon]) to identify whether fishing habitats are susceptible to periods of low pH and/or high temporal pH variability. This information will allow us to identify specific populations of commercially important species that may be at risk*.*

# BROADER IMPACTS OF THE PROPOSED WORK

This project will result in a new commercially available glider sensor suite for the planned national glider network. We will deliver high spatial and temporal resolution *in situ* pH measurements in commercially important coastal regions along the U.S. NES where ocean pH information is critically needed. Integration of simultaneous measurements from multiple sensors on one glider will allow us to distinguish interactions between the physics (temperature), chemistry (salinity, dissolved oxygen), and biology (fluorescence, backscatter) of the ecosystem. This will provide the foundation of what could become a real-time national coastal pH monitoring network with the capability of serving a wide range of users including academic and government scientists, monitoring programs including those conducted by OOI, IOOS, NOAA and EPA, water quality managers, and commercial fishing companies. The open accessible, automated real-time data would provide a warning system that would assist scientists studying ecological processes, water quality managers and conservationists to monitor impacts, and commercial operators to implement adaptive strategies. Mitigation strategies to date include shutting off intake seawater valves or adding sodium carbonate to increase the pH and aragonite concentration in the incoming seawater. The latter has been successful for the Taylor Shellfish Hatchery in Dabob Bay, Washington. Since the initiation of consistent water quality monitoring, including pH, near the hatchery in 2010, they have implemented an automated system to control the injection of sodium carbonate into the main intake pipe with great success in oyster larval growth and survival.

The data resulting from this newly developed technology will help to create a baseline and allow for the tracking of these important environmental changes in over time. It will allow us to identify habitats that are susceptible to periods of low pH and/or high temporal pH variability that will assist researchers and stakeholders to better understand the direct effects and significant ramifications ocean acidification will have to commercially valuable species such as wild stocks of sea scallops, clams, and lobsters which all have shown to be sensitive to ocean acidification (Berge et al. 2006, Gazeau et al. 2007, Beesley et al. 2008, Green et al. 2009, Talmage and Gobler 2009, Keppel et al. 2012, Kroeker et al. 2013, Waldbusser et al. 2011a,b, Waldbusser et al. 2013).

Finally, data resulting from this project and future applications can help build and improve ecosystem models. A range of data assimilative modeling systems has matured rapidly over the last decade in the ocean science community. Many of these systems are being configured to assimilate glider data (temperature and salinity) (i.e., ROMs). The technology produced from this project will enable the development of coastal forecast models with the capability to predict the variability and trajectory of the low pH water.

*Education and Outreach*

Our outreach and education effort will focus on graduate student mentoring, undergraduate teaching, and the fisheries community. First, our education effort will be on traditional pedagogical efforts. A multitude of U.S. reports link Science, Technology, Engineering, and Mathematics Education (STEM) to the future security and economic success of the United States (President’s Council of Advisors on Science and Technology 2010, U.S. Department of Commerce 2012). This project in the STEM field will be central to a graduate student’s thesis and will support a minimum of two undergraduate students. Our mentoring practices will be focused on providing active mentorship to provide the skills, knowledge and experience by having the students work as part of science leadership team and be actively engaged in the field planning/implementation/synthesis. Secondly, we will benefit from on-going involvement in MARACOOS and collaborations with NOAA and industry to establish dialog with their collaborative commercial fisheries contacts. Our goal here is not only to inform them of the project and involve them in using the data output, but also to begin fruitful discussions regarding the development of a long-term strategy to building a national pH monitoring system, identification of potential vulnerable populations, and potential mitigation options to low pH water.

# RELEVANT BACKGROUND OF INVESTIGATORS TO PROPOSED WORK

Grace Saba (Rutgers University), Managing Faculty of Rutgers University Center of Ocean Observing Leadership (RUCOOL), will serve as the Lead Investigator on the project. She will be responsible for planning and implementation of proposed research, testing of equipment, planning glider flights, and analyzing carbonate chemistry data in relation to fisheries habitats. Saba will advise one graduate student and two undergraduate students.

Travis Miles (Rutgers University), Managing Faculty of Rutgers University Center of Ocean Observing Leadership (RUCOOL), will serve as the glider data analysis expert. He is responsible for developing glider deployment plans, performing deployments and recoveries, and performing post- deployment data processing and analysis as well as visualization.

Wei-Jun Cai (University of Delaware) will be responsible for sample analysis of carbonate chemistry parameters, comparison with DuraFET pH, and data synthesis. He will advise a Ph.D. student (K. Mike Scaboo) on this work.

Subcontracts (through Rutgers University) are a critical component of this proposed research.

Clayton Jones will lead the efforts of Teledyne Webb Research. His responsibilities on this project include adapting a payload of a Slocum Webb glider for the Satlantic Deep-Sea DuraFET profiling pH sensor. This will include working closely with Sea-Bird Scientific and modifying custom payload hardware and firmware for the duration of the project. He will also be integral in preparing this new glider payload/sensor pair for product release. Andrew Barnard will lead the efforts from Sea-Bird Scientific, which includes Sea-Bird Electronics, Satlantic, and WET Labs. Via coordination with Teledyne Webb Research, Sea-Bird Scientific will develop a Deep-Sea DuraFET profiling pH sensor for integration in the science bay module of the Slocum Glider. They will provide technical support for operation and maintenance of the delivered systems for the duration of this project.

# PROJECT MANAGEMENT TIMELINE

The major tasks and responsibilities are outlined below. Graduate and undergraduate students and collaborators will also be actively involved in each of these tasks.

|  |  |  |  |
| --- | --- | --- | --- |
| **Objective** | **Year 1** | **Year 2** | **Year 3** |
| Integrate Deep-Sea DuraFET pH sensor into glider (along with CTD, Ecopuck, and Optode) | X |  |  |
| Test flight #1 and *in situ* calibration of multiple sensors |  | X |  |
| Troubleshooting (if necessary) |  | X |  |
| Test flight #2 and *in situ* calibration of multiple sensors |  | X |  |
| Long-term glider deployment (60 days): High resolution mapping of pH in the MAB and initial cross-calibration of sensors with in situ samples collected from small vessels and during ECOA II research cruise |  | X |  |
| Initiate integration of real-time data into RUCOOL, MARACOOS, and THREDDS |  | X |  |
| Data assimilation and analysis; Manuscript preparation |  | X | X |
| Commercialize Deep-Sea DuraFET pH sensor for gliders |  |  | X |