PAPER

A Regional Slocum Glider Network in the Mid-Atlantic Bight Leverages Broad Community Engagement

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ABSTRACT

Autonomous underwater gliders have proven to be a cost-effective technology for measuring the 3-D ocean and now represent a critical component during the design and implementation of the Mid-Atlantic Regional Ocean Observing System (MARCOOS), a Region of the U.S. Integrated Ocean Observing System. The gliders have been conducting regional surveys of the Mid-Atlantic (MA) Bight, and during the 3 years of MARCOOS, the glider fleet has conducted 22 missions spanning 10,867 km and collecting 62,824 vertical profiles of data. In addition to collecting regional data, the gliders have facilitated collaboration for partners outside of MARCOOS. The existence of the MA glider observatory provided a unique test bed for cyber-infrastructure tools being developed as part of the National Science Foundation's Ocean Observatory Initiative. This effort allowed the Ocean Observatory Initiative software to integrate the MARCOOS assets and provided a successful demonstration of an ocean sensor net. The hands-on experience of the MA glider technicians supported training and provided assistance of collaborators within the Caribbean Regional Association, also a region of the U.S. Integrated Ocean Observing System, to assess the efficacy of gliders to resolve internal waves. Finally, the glider fleet has enabled sensor development and testing in a cost-effective manner. Generally, new sensors were tested within the MARCOOS domain before they were deployed in more extreme locations throughout the world's oceans. On the basis of this experience, the goal of the MARCOOS glider team will be to expand the MA network in coming years. The potential of how an expanded network of gliders might serve national needs was illustrated during the 2010 Macondo Gulf of Mexico oil spill, where gliders from many institutions collected subsurface mesoscale data to support regional models and oil response planning. The experience gained over the last 5 years suggests that it is time to develop a national glider network.

Keywords: Webb gliders, IOOS, Ocean observatories

Introduction

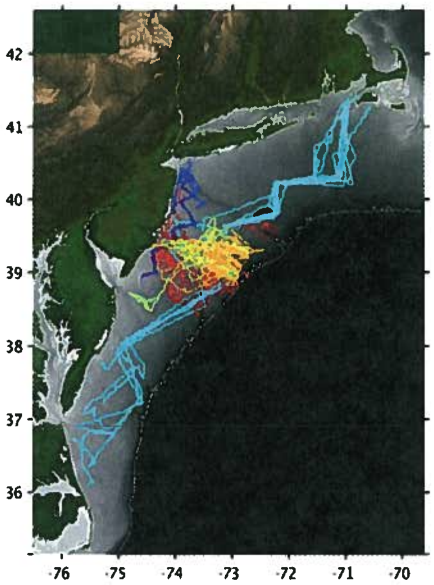
The Mid-Atlantic (MA) region, spanning from Massachusetts to Cape Hatteras, contains an extremely productive continental shelf supporting diverse and abundant fin and shellfish populations (Gates, 2009). The MA is characterized by a broad continental shelf that extends out for several hundred kilometers. The MA exhibits considerable seasonal and interannual variability in temperature and salinity (Mountain, 2003), which has a great influence on the abundance and distribution of its living resources. Seasonal hydrographic dynamics of the MA underlie many of the evolved life strategies of resident species that are evidenced by regional migrations and breeding dynamics. For example, the breeding success of many fish and shellfish are tied closely to overall hydrography off the MA (Weissberger and Grassle, 2003; Ma, 2004; Ma & Grassle, 2004; Lazzari & Able, 2006; Manderson, 2008). Therefore, understanding the dynamics of the MA ecosystem requires at minimum an understanding of the seasonal evolution of hydrographic features and preferably enough temporal/spatial information over the year to resolve the quantitative importance of episodic effects. Increasing our understanding of these processes is critical for the development of any ecosystem-based management strategy, which is extremely important as the MA hydrography (Mountain, 2003) and ecosystem (Schofield et al., 2008) appears to have changed over the last few decades.

Efforts to understand the seasonal dynamics of the MA has been a major research focus for decades (Walsh et al., 1988a,b; Biscaye et al., 1994). These research efforts have relied on ships (Walsh et al., 1988a,b; Mountain, 2003), moorings (Biscaye et al., 1994), satellites (Yoder et al., 2001, 2002; Ryan et al., 1999, 2001; Moline et al., 2004), and high-frequency (HF) radar (Gong et al., 2010). Satellites and HF radar provide a regional perspective and collect data continuously throughout the year; however, they only provide data on surface waters, which is problematic as the MA is characterized by a great deal of subsurface variability. In late spring and early summer, a strong thermocline develops across the entire continental shelf, isolating from the surface a continuous mid-shelf "cold pool" of water that extends from Nantucket to Cape Hatteras (Houghton et al., 1982). This stratification forms one of the most extreme coastal thermoclines on Earth with temperatures ranging from 30° at the surface to 8°C below the thermocline. The thermal gradient is very sharp with the majority of the change occurring within 5 m (Biscaye et al., 1994). Many of the biological features of interest reside at or below the thermocline, which is below the detection limits of satellites and HF radar. Ships can provide detailed 3-D data (through profiling and undulating instrument platforms); however, the expense of the ship operations limits the temporal coverage. Moorings can collect HF temporal data, although the maintenance and operations costs prohibit a sufficient number to be deployed that could resolve the spatial variability. Therefore, there is a critical need to deploy new technologies that can routinely provide a regional sustained presence at sea. Autonomous underwater gliders have proven to be a robust technology (Davis et al., 2003; Schofield et al., 2007; see Figure 1), which is why they were specifically chosen as a critical component during the design and implementation of the Mid-Atlantic Regional Ocean Observing System (MARCOOS), a region within the U.S. Integrated Ocean Observing System (IOOS®).

This manuscript will describe the glider efforts within MARCOOS. We will highlight the science motivations of the glider network and the current metrics (number of missions, costs) of the glider network. We will also provide three examples of how the gliders provide a unique capacity that has allowed MARCOOS to collaborate with science communities outside the MA. Finally, we look to future glider efforts as MARCOOS matures and argue that this and other regional glider programs will provide the foundation for a national glider network for United States.

FIGURE 1

The Webb glider tracks for deployments in the MA Bight since October 2003. Each color represents a different funding source. The turquoise lines represent joint deployments between ONR's ESPreSSO program and NOAA's MARCOOS program. The red lines represent the deployments associated with the Rutgers Endurance Line. The orange lines represent the glider deployments associated with the ONR's Shallow Water 2006 experiment. The green lines are associated with NSF's OOI Observing simulation experiment in November 2009. The light blue lines near New York Harbor represent deployments associated with the NSF Langragian Transport and Transformation Experiment. The dark blue lines are deployment funded by the State of New Jersey focused on conducting water quality surveys. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2010/00000044/00000006.)



History and Motivations for the MARCOOS Glider Network

The regional glider efforts grew out of the Rutgers Endurance time series transect, which began in Fall 2003 (Glenn & Schofield, 2009). The endurance transect is a cross-shore survey from offshore Tuckerton, New Jersey, to the edge of the continental shelf and has been conducted as many times as possible as funds allowed over the last 7 years. To date, there have been 55 glider missions flown along the Endurance line since October 2003, collecting surveys more than 18,000 km from 826 glider-days at sea (Table 1). It has provided data allowing a full characterization of the seasonal dynamics offshore New Jersey (Castelao et al., 2008a,b, 2010a,b). It should be noted that this effort has been conducted with no formal funding award to maintain the time series. When MARCOOS was funded, the goal was to expand Endurance glider surveys to span the waters from Massachusetts to Cape Hatteras.

One scientific motivation for this effort was to provide a foundation to support ecosystem decision support. In the MARCOOS region, direct, indirect, and induced economic impacts of commercial and recreational fisheries are substantial, with the dockside value of commercial marine fish landings averaging approximately $1 billion/year and annual spending on recreational coastal and ocean fishing being estimated at $7.4 billion. The long-term economic value of fisheries would be increased if managers could prevent overfishing; however, uncertainty about the status of fish stocks and about how ocean conditions influence fish population dynamics and fishing success limit current management practices. Efforts are underway to develop "ecosystem-based fishery management" and "spatial marine planning." Both approaches rely on near synoptic ocean observations collected over ecologically relevant scales (spatial scales of meters to hundreds of kilometers, temporal scales of days to years) to better characterize the fishery dynamics. Defining habitat indicators for fishery resources is challenging because of the complex interactions between marine ecosystems and physical forcing; however, preliminary research efforts suggest that MARCOOS data can increase the explanatory power of habitat models (Palimera, personal communication). One of the most important subsurface physical features that structures fisheries on the MA is the cold pool water (CPW), which is spatially and temporally variable (Bignami & Hopkins, 2003). The CPW is the lowest temperature water and seasonally contains significant chlorophyll (Wood et al., 1996), and its location can affect the migration and spawning behavior of many fish (Sullivan et al., 2005).

Gliders provide a useful tool for collecting data on the CPW, which is not detectable by remote sensing techniques. They also provide data that can support numerical modeling via data assimilation. Past coastal predictive skill experiments have emphasized the importance of resolving the source waters (i.e., the upstream condition) to the model domain (Wilkin et al., 2005). This required that surveys span the entire MARCOOS domain, which require two separate glider missions to be conducted, because the standard glider batteries (alkaline) do not have sufficient energy to survey the entire MA; however, recently lithium batteries have been used and have sufficient

TABLE 1

The data collected by Webb Slocum gliders on the MA Bight. There were three major classes of missions. The first was the Rutgers Endurance line. The second was the surveys of the MA conducted by the IOOS and the Office of Naval Research's ESPreSSO program. The final class of MA glider missions was individual research projects. Some of the glider numbers collected by those individual research programs is also listed.

Mission	No. Missions	Glider-Days at Sea	Vertical Casts	Kilometers
Endurance line	55	826	159,011	18,028
MA surveys[a]	22	493	62,824	10,867
Research Projects	29	500	90,413	9,543
OOI[b]	4	74	23,332	1,673
SW06[c]	17	356	51,933	6,683
LATTE[d]	6	50	10,041	871
NJ DEP[e]	2	20	5,107	316
Total	106	1,819	312,248	38,438

[a] The glider surveys of MA Bight conducted by the Office of Naval Research's ESPreSSO and the IOOS MARCOOS programs.

[b] The glider surveys associated with the NSF's OOI.

[c] The glider surveys associated with the Office of Naval Research Shallow Water 2006 experiment.

[d] The glider surveys associated with the Lagrangian Advection Transport and Transformation Experiment.

[e] The glider surveys associated with the New Jersey Department of Environmental Protection coastal hypoxia surveys.

energy to survey the entire region. The drawback of the lithium batteries is the increased cost. For the alkaline surveys, one of the missions begins in southern Massachusetts and conducts a series of cross and along shore transects to central New Jersey. A second survey is typically conducted from central New Jersey to the mouth of Chesapeake Bay. Funding leveraged between the IOOS Program in the National Oceanic and Atmospheric Administration (NOAA) and the Office of Naval Research (ONR) Experimental Shelf Predictive Shelf-Slope Optics (ESPreSSO) program, allowed us to begin conducting MA surveys. To date, these programs have supported us to conduct 22 missions spanning 10,867 km while collecting 62,824 vertical profiles of data. The surveys were timed to coincide with the northeast National Marine Fishery Survey cruises.

The extensive glider experience in MA provides a basis for assessing the cost-effectiveness of these technologies. Cost estimates for glider missions are based on a full-time dedicated glider technician ($411 per day[1]), the coastal vessels for glider deployment and recovery,[2] and the expenses for batteries/Iridium/insurance/nominal maintenance and repair.[3] The estimated costs for MA operations assumes for each mission a dedicated technician for each day the glider is deployed as well as the deployment/recovery and ancillary expenses. Note, however, that a single technician can monitor many gliders when deployed, and the gliders represent cost-effective scalable technology. During past experiments, a single technician has monitored up to eight gliders. These estimates do not include support for the development of new hardware or software. On the basis of the MA deployment of gliders for 1,819 days, the costs are $1,815,534. This simplifies to $6 per vertical profile, $47 per kilometer traversed, and $998 per day. These costs compare favorably with research class vessels (nominal cost ~$25,000 per day) and a smaller coastal vessel ($1,500 per day) in which daily glider costs are 4% and 66% of comparable ship rates, respectively. Gliders cannot replace ships, which remain the most modular and flexible ocean sampling platform available to oceanography that far exceeds the current capabilities of existing sensors for gliders. Therefore, we recommended that gliders in near future take over the coastal monitoring needs, which would free up ships to conduct more sophisticated adaptive sampling without needing to dedicate time to ocean mapping.

Collaboration Beyond the MARCOOS Domain

A major advantage of having a robust glider effort in the MA is that it has provided a means to galvanize collaborations from outside the MARCOOS community. MARCOOS (1) provides an existing open access observatory for users, (2) has a large pool of technical experience that can assist other groups in building observatories, and (3) provides a cost-effective test bed for new technologies. The benefits to MARCOOS are that this helps ensure that new technologies from external groups are integrated into the existing network and help develop a larger cohesive distributed ocean observatory community that provides a national resource (see below in future directions).

MARCOOS Provides an Existing Observatory

The MARCOOS glider network provides a test bed for partners external to the MA. One good example of this was demonstrated in November 2009 when the MARCOOS supported the U.S. National Science Foundation's (NSF) Ocean Observatory Initiative (OOI). A significant focus of the OOI is on developing a sophisticated cyberinfrastructure (CI) that links physical ocean observatories, computation, modeling, storage, and network infrastructure into a coherent system of systems. The software also provides a Web-based social network enabled by real-time visualization and access to model outputs allowing for adaptive sampling science. To ensure the development of a useful CI, a "spiral design strategy" is being used encouraging the oceanographic community to provide input during the construction phase. MARCOOS provided an existing test bed with a wide range of streaming data and an existing glider fleet that could be used to test the planning and prosecution software (Schofield et al., 2010).

The goal of the November experiment was to assess how well the CI software can aggregate data from ships, autonomous underwater vehicles, shore-based radars, and satellites and to make it available to ocean forecast models. Scientists used the model forecasts to guide future (next 24 h) glider missions, which then were used to coordinate satellite observing to demonstrate the feasibility of two-way interactivity between the sensor Web and predictive models. A distributed community of MARCOOS scientists provided the OOI CI team with daily adaptive guidance for a task-able satellite, using information from a fleet of four MARCOOS gliders.

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[1] The costs include salary, fringe, and university indirect cost return.

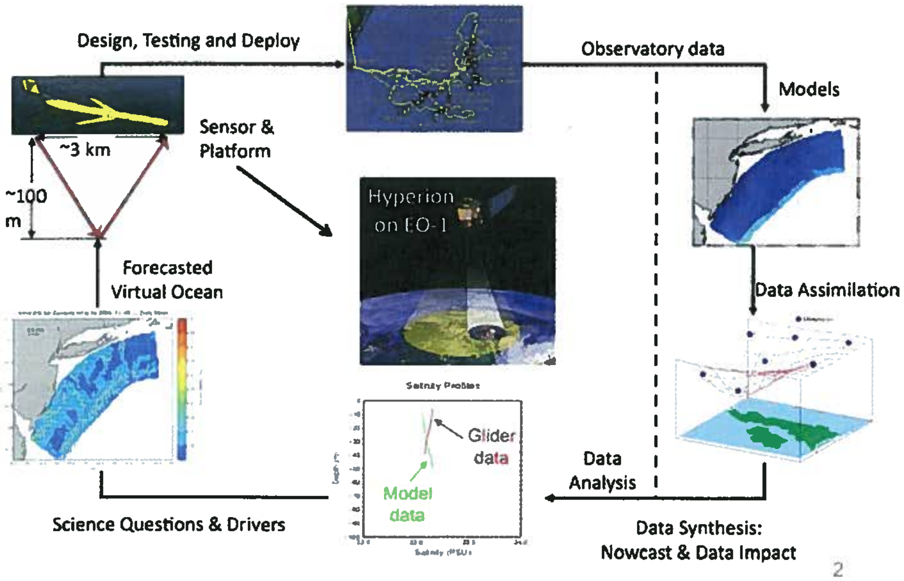
[2] We have taken a high-end estimate of $4,000 per day for ships for deployment and recovery.

[3] We place the total upper end of costs for coastal waters at $10,000 per mission.

The OOI software was being developed to enable operators to monitor and control individual components within an ocean observing network. The CI software coordinates and prioritizes the shared resources, allows for the semi-automated (Thompson et al., 2009, 2010) reconfiguration of asset tasking, and thus enables an autonomous execution of observation plans for the fixed and mobile observation platforms (Figure 2). For this effort, numerical model ocean forecasts allowed the simulation of future *in situ* robot trajectories, which could be used by a distributed group to optimize sampling on the basis of the science needs (Figure 3) and the practicability of moving gliders efficiently in the resolved current field (e.g., were targets actually "reachable"?) (Thompson et al., 2009, 2010). Thus, the CI software could deliver the community science needs back to the *in situ* observation network in a timely manner. The CI software coordinated sampling between underwater gliders and the space-based Hyperion imager flying on the Earth Observing One (EO-1) (http://eo1.gsfc.nasa.gov) spacecraft leveraging the Earth Observing Sensorweb (Chien et al., 2005, 2008) capability. The Hyperion images are typically 7.5 km (across track) by more than 100 km (along track) and resolve 220 spectral bands from 0.4 to 2.5 microns with a spatial resolution of 30 m. This small spatial footprint makes it difficult to ensure *in situ* assets are present for calibration. The Hyperion is a task-able platform and therefore an alternative approach would mobilize *in situ* assets and simultaneously adjust the satellite swath to be coincident. During the field experiment, observational data and multimodel forecasts were analyzed to determine the tasking location for the satellite. These coordinates were used by the EO-1 Web capability (http://sensorweb.jpl.nasa.gov) to retask the spacecraft. The 48-h model forecast was then used by the CI software to plan the optimal path to colocate any gliders within the tasked EO-1 Hyperion swath. Two MARCOOS gliders were successfully moved within the narrow Hyperion swath, which is only 7.5 km wide, whereas other gliders were diverted outside the swath to accomplish other science missions (Figure 4). This represents a major technology breakthrough in simultaneously coordinating satellite and underwater assets guided by multimodel forecasts. It provided a machine-to-machine interactive loop driven by a geographically distributed group of scientists.

FIGURE 2

The machine-to-machine data flow during the OOI's Observation Simulation Experiment. A fleet of gliders was informed by model-driven forecasts to optimize science sampling being conducted by a geographically distributed team of scientists. The observatory data were assimilated by an ensemble of numerical forecast models that were used to optimize the glider sampling. Optimized glider data were also used to adjust the data collected by the Hyperion EO-1 satellite.



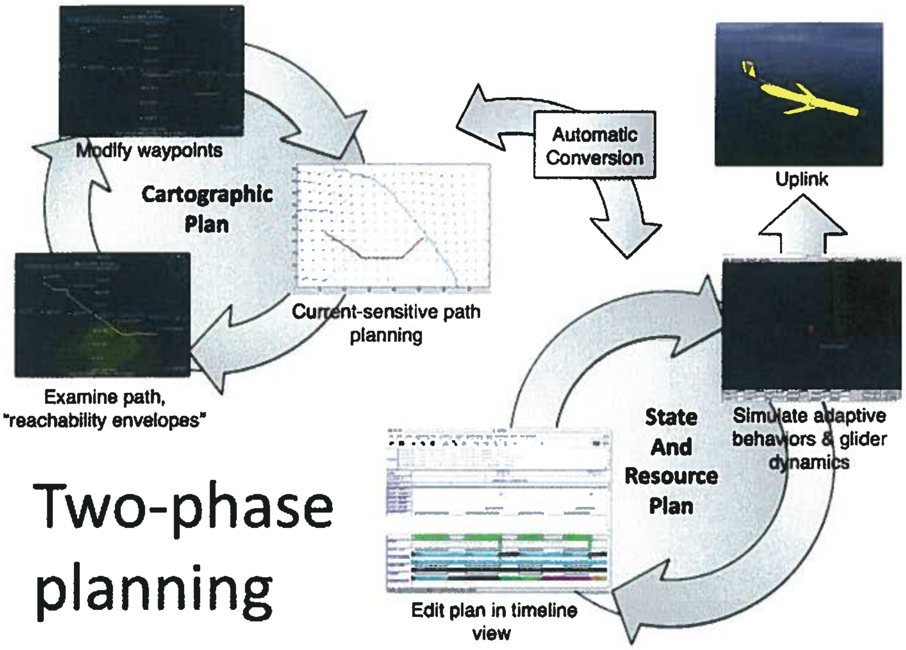
Partnership with Other IOOS Partners

The extensive pool of expertise within MARCOOS provides a resource to the wider IOOS community. This has been particularly true for glider operations where the community is small but rapidly growing. Through funding from the ONR Environmental Optics program, formal glider training sessions have been developed and have provided training to researchers from within the MARCOOS, international universities, NATO, and the Naval Research Laboratories. Here we highlight the partnership between MARCOOS and the IOOS CAribbean Regional Association (CARA). MARCOOS and CARA have partnered in sharing expertise in both the installation of HF radar and the deployment of Webb gliders.

The focus of the glider efforts in the Caribbean (Figure 5A) was on studying mixing processes in the coastal waters

FIGURE 3

The automated planning prosecution tools used by glider operators during the OOI CI test. The automated software involves a two-phase planning strategy. One component is a cartographic planner that allows glider operators to examine the "reachability envelopes" of a glider on the basis of the currents forecasted for the future ocean. This provides a tool for scientists to modify glider waypoints to assess if they can reach proposed goals in a specified amount of time. This is coupled to an automated state and resource planner. The state and resource planner allows the user to simulate different mission strategies to make wise strategic decisions, which are then uploaded to the glider as a series of waypoints. The state and resource planner not only keeps track of the physical state of the glider (remaining battery power) but also other features that need to be considered by the operator (commercial shipping lanes). The net result is that the scientist can optimize the science missions to collect the highest possible quality data.



offshore Puerto Rico (Figure 5B). Internal tides, vertical oscillations of the pycnocline, can promote ocean mixing (St. Laurent & Garrett, 2002), modulate phytoplankton productivity (Evans et al., 2008), induce biological aggregations (Lennert-Cody & Franks, 1999; Moore & Lien, 2007), cause shelf break "scouring," modulate deep coral reef biology, and induce coastal seiching. Prior studies of internal tides in the Mona Passage between Puerto Rico and Hispaniola, initially driven by interest in billfish aggregations at the site, have shown that the Mona Passage and the shelf break along the SW coast of Puerto Rico are sites of internal wave generation. These phenomena have been partially characterized through the work of Bejarano (1997), who documented large-amplitude internal tides in the Mona Passage, by Teixeira (1999), who looked deeply into associated seiches and their excitation, and to Alfonso-Sosa (2001), who explored the local generation of internal tides through the action of tides impinging stratified waters on topographic slopes. In summary, these interfacial tides are approximately in phase with the astronomical tide, are of semidiurnal frequency, and exhibit amplitudes of up to 50 m (Teixeira & Capella, 2000).

Glider-based observations in the Mona Passage were used to characterize internal waves revealing the periodic generation of a wave train spanning the entire passage. Wave generation occurs in the region of "El Pichincho," a submerged ridge across the passage where tidal action induces hydraulic forcing of the wave (Figure 5B). Here, semidiurnal isopycnal displacement centered at depths around 100 m spans a vertical range of up to 50 m. Density sections along the glider transects to the south of the suspected generation site reveal a gradient of decreasing wave amplitude suggesting damping of the wave along its southward propagation axis toward the open Caribbean Sea (Figure 5C).

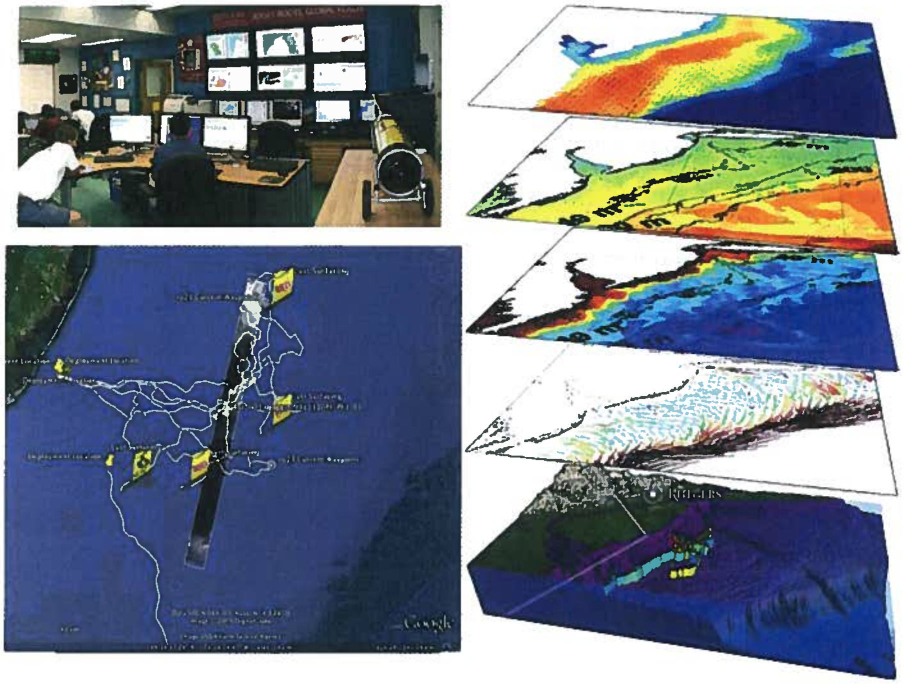
Chlorophyll sections for two transects (Figure 5D) show significant modulation of phytoplankton biomass within the subsurface chlorophyll maximum (SCM). We propose that this modulation is brought about by the spatial and temporal variation of the irradiance field, resulting from the vertical displacements of the SCM and the diurnal cycle. This hypothesis is supported by the correspondence between chlorophyll *a* concentration at the SCM and the depth of the pycnocline. These joint IOOS glider observations prompt us to propose that Caribbean passages may be the main source of internal tide energy prevalent throughout the Western North Atlantic.

MARCOOS Provides a Sensor Test Bed

The MA Webb gliders allow MARCOOS to act as a test bed for new sensors. The MA provides a location where the community has extensive experience as well as existing facilities that allow for field calibration of new sensors with ongoing operations. Sensors developed by funding from the ONR, the National Ocean Partnership

FIGURE 4

The IOOS observatory backbone that supported the OOI effort. The right-hand column shows the regional data provided by IOOS. The data included subsurface data from gliders, regional CODAR surface currents, ocean color and sea surface temperature remote sensing, and an ensemble of five numerical models. The data were coordinated and distributed over the world wide web via the Rutgers Coastal Ocean Observation (upper panel on left column) to the science/engineering teams distributed throughout the country. The bottom-left panel shows the Hyperion data swath that was collected after the ocean observatory directed the tilt of the satellite.



Program, the Environmental Protection Agency (EPA), the NSF, and the Gordon and Betty Moore Foundation have provided new sensor packages that were then first tested in the MA. These sensors are typically tested and refined in the MA before being deployed in more extreme locations that cannot provide the logistical support available within the MA. Initial testing and deployment of sensors aboard the gliders in the MA that have occurred over the last 5 years include development of physical sensors (acoustic Doppler current profilers, turbulence shear probes), optical instruments (backscatter sensors, multispectral radiometers, light attenuation sensors, light scattering sensors, hyperspectral spectrometers, cameras), fluorometers (chlorophyll, colored dissolved organic matter, fast repetition rate chlorophyll), oxygen sensors, and passive acoustic sensors (Glenn & Schofield, 2009). In addition, the glider test bed has supported the development of customized lithium batteries (Glenn et al., 2010), improved onboard computing (Woithe et al., 2010), new glider tail technologies (Glenn & Schofield, 2009), antifouling skin (Lobe et al., 2010), and extended payloads (Glenn & Schofield, 2009). Sensors that have been initially tested have then anchored missions along many of the North American coastlines (Chao et al., 2008; Glenn et al., 2008; Schofield et al., 2008), North Atlantic (Glenn et al., 2009), Pacific Northwest, Caribbean, Antarctica (Kahl et al., 2010), Baltic, Norwegian fjords, Sargasso Sea, and Alaska.

Future Directions

On the basis of the experience gained during the last 3 years of IOOS, the MARCOOS team has identified several key goals for the next 5-year effort. Within the MARCOOS domain, future strategies call for expanding the glider presence beyond a single seasonal survey each year. This need is based on one of the original goals of the MARCOOS gliders to assist in ecosystem-based management, which determined that defining the CPW was a critical need. Although the initial regional glider surveys could resolve the CPW, they could not resolve the formation, dynamics, and dissipation of the CPW; this calls for an aggressive expansion of the existing time series glider lines. This effort will require an expanded fleet of MARCOOS gliders (note MARCOOS currently owns one Webb glider) and increasing the surveys from a seasonal effort to a monthly time series. The high-resolution time series will enable numerical modeling of the CPW, which can resolve the dynamics in the MA.

IOOS represents the framework within which to establish a national backbone of ocean observation capabilities. This backbone is critical for overcoming the chronic undersampling of the coastal waters of the United States. The cost-effectiveness of gliders offers the potential to establish a cost-effective national backbone for subsurface spatial observations while HF radar and satellites complete the surface picture. The importance of developing a national capacity was clearly illustrated during the Deepwater Oil spill disaster (http://rucool.marine.rutgers.edu/deepwater/), when the paucity of subsurface measurements hindered response planning to the oil spill. This gap was addressed when a wide range of federal (U.S. Navy), commercial (iRobot, Teledyne Webb Research), and academic partners (Applied Physics Lab, Mote Marine Laboratory, Rutgers, Scripps Institution of Oceanography (under the IOOS Region–Southern California Coastal Ocean Observing System), University of Delaware, University of South Florida (under the IOOS Regions South Eastern Coastal Ocean Observing Regional Association and Gulf of Mexico Coastal Ocean Observing System), and Woods Hole Oceanographic Institution) joined forces and provided a fleet of gliders to make subsurface maps of the Gulf of Mexico (Figure 6). The gliders provided months of subsurface data, which would have been prohibitively expensive to collect using ships. Although the partners provided gliders, they came at the expense of their individual research efforts within their local waters; therefore, there is a critical need to develop the national capacity so the regional time series can be collected, the ocean modeled, and the assets tasked. There is a great need to develop a capacity to efficiently deal with events of national importance in the future. Additionally, strong partnerships with technology development initiatives, such as the OOI, are critical to ensure that despite the operational focus of IOOS, it is continuously infused with maturing technology that will provide expanded functionality to the growing network. Using these new technologies will make deploying a national glider fleet achievable and represents a cost-effective investment for IOOS.

FIGURE 5

The collaborative glider efforts between MARCOOS and CARA were crowned with joint deployments of the MARCOOS glider in Puerto Rican waters. (A) The CARA and the MARCOOS team members congratulating each other after the glider is deployed offshore (which can be seen in the white circle). (B) The glider transect into the Mona passage offshore Puerto Rico. (C) The glider measured density showing large internal waves. (D) The glider measured chlorophyll showing the phytoplankton concentrations being enhanced in the region of high internal wave activity.

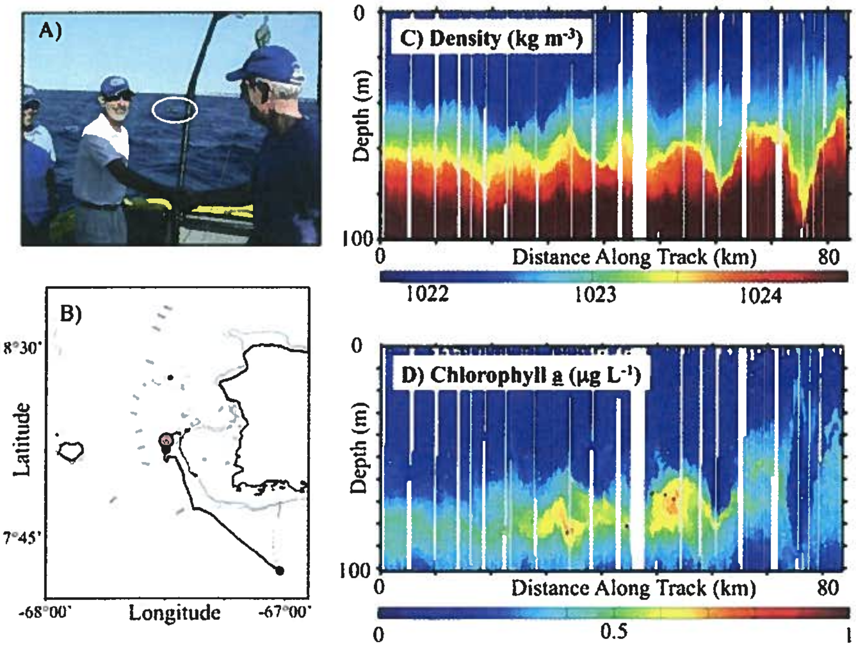
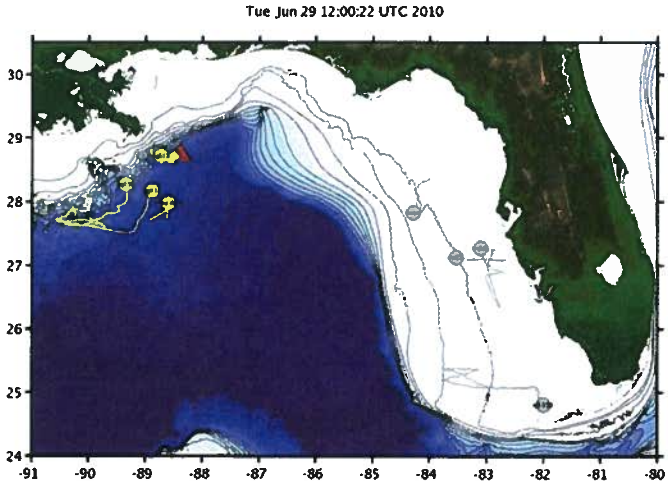


FIGURE 6

The positions of a community of gliders (yellow and gray circles) in the Gulf of Mexico on June 29, 2010. The glider fleet was assembled by community in response to the Deepwater oil spill. The community of partners included the U.S. Navy (sg135 and sg137), the Scripps/WHOI (spray-00-48), the iRobot/Applied Physics Lab (sg515), the University of South Florida (bass), the Rutgers University (ru23), the Mote Marine Laboratory (Waldo), and the University of Delaware (ud-134).



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