PAPER

The Trans-Atlantic Slocum Glider Expeditions: A Catalyst for Undergraduate Participation in Ocean Science and Technology

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ABSTRACT

Results of Office of Naval Research (ONR)- and National Science Foundation (NSF)-sponsored collaborative coastal science experiments using underwater gliders were reported at the E.U./U.S. Baltic Sea conference in 2006. The National Oceanic and Atmospheric Administration (NOAA) recognized the parallel educational potential and issued a trans-Atlantic challenge—modify one of the coastal gliders and fly it across the Atlantic, entraining and inspiring students along the way. Leveraging the experience of the NSF Centers for Ocean Sciences Education Excellence, a needs assessment process guided the development of a new undergraduate research program based on the cognitive apprenticeship model. The generalized model was applied to the specific opportunities provided by the trans-Atlantic challenge, involving students in every aspect of the missions. Students participated in the modifications and testing required to increase glider endurance and in the development of the mission planning tools. Scientist and student teams conducted three long-duration missions: (1) RU15's flight from New Jersey to Nova Scotia to test the lithium batteries and ruggedized fin technology in storms, (2) RU17's first attempt at the Atlantic crossing that provided the lessons learned, and (3) RU27's successful trans-Atlantic flight a year later. Post-flight activities included development of new intuitive glider data visualization software that enabled students to analyze the glider data and compare it with ocean forecast models, enabling students to create their own new knowledge. Lessons learned include the significant gains achieved by engaging students early, encouraging them to work as teams, giving them the tools to make their own discoveries, and developing a near-peer mentoring community for increasing retention and diversity. The success has inspired an even broader vision for international glider missions, that of a glider-enabled global classroom to repeat the track of the HMS *Challenger* and its first scientific circumnavigation of the globe.

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Introduction

The field of oceanography is shaped by a rich history of expeditionary science. The inspiration provided by our short times at sea has spurred the imagination and creativity of ocean scientists for centuries, prompting us to imagine and implement new approaches for exploring, observing, understanding, and utilizing the world's oceans. One vision from 22 years ago (Stommel, 1989) was that of a global ocean patrolled by Slocum underwater gliders guided by satellite data and numerical model forecasts. In Hank Stommel's futuristic world, support for the network was galvanized by a 198-day trans-Atlantic flight of the glider *Sentinel 1* from Bermuda to northwest Africa. The mission was flown by researchers working from an attic control room in the Woods Hole Oceanographic Institution's Bigelow Building. At that time in Woods Hole's history, the attic of Bigelow was occupied by oceanography students.

Since that inspirational vision was published, ocean glider technology has matured and now routinely anchors scientific experiments, enabling scientists to conduct sustained and adaptively adjusted science missions (Davis et al., 2003; Schofield et al., 2007). The adaptive sampling capabilities of the gliders are enabled by their ability to navigate relative to the flow and the two-way communications provided by the global Iridium network, allowing glider data to be sent to control centers on shore and new sampling commands to be sent back to the gliders at sea. As ocean observatories continue to mature, coordinated fleets of gliders are growing contributors to the National Oceanic and Atmospheric Administration (NOAA)-led U.S. Integrated Ocean Observing System (IOOS®) (Schofield et al., 2010a), the National Science Foundation (NSF) Ocean Observing Initiative (OOI) (Schofield et al., 2010b), and the Navy's Littoral Battlespace Sensing-Glider (LBS-G) initiative. These initiatives and others are implementing what Walter Munk termed the 1 + 1 = 3 scenario for ocean sampling (Munk, 2000), where a new ocean omnipresence is enabled by satellites in space combined with vast in-water arrays of drifting profilers, gliders, and time series stations. The approach not only offers researchers new opportunities for ocean science but also provides a potential mechanism to share the real-time excitement of exploration and scientific discovery with students and the public.

The educational value of the gliders was recognized by NOAA leadership in May of 2006 at the E.U./U.S. sponsored conference promoting international collaborations in the Baltic Sea. NOAA responded to the growing number of glider presentations with a challenge to take one of the existing gliders, modify it, and fly it across the Atlantic, entraining and inspiring students along the way. It was presented as a response to the *Rising Above the Gathering Storm* (2007) report's observation that while the vitality of the U.S. economy depends on the scientific and technological innovations of a well-educated workforce, U.S. economic leadership was eroding partly because of the decreasing number of students choosing science, math, and engineering careers. The trans-Atlantic glider mission was viewed as an opportunity to re-spark interest in science and technology, invigorate student involvement, and influence their career path. It was considered high risk but, with the proper visibility, capable of producing high rewards.

Rutgers scientists attending the Baltic Sea conference viewed NOAA's trans-Atlantic challenge as an opportunity to develop a new educational program enabled by the gliders. Participation in high-risk ocean-scale glider expeditions would provide opportunities for students to directly experience the many difficulties of operating at sea, the value of perseverance and teamwork, and the feeling of accomplishment when successful. Students would experience the excitement of discovery through the analysis of data they helped collect from harsh environment, and they would gain a more global cultural perspective by communicating with scientists and students from around the world.

This led Rutgers, Teledyne Webb Research, and their international partners to conduct three long-duration glider missions in 2008–2009. The first extended-duration mission of the series, glider RU15's flight from Tuckerton, New Jersey to Halifax, Nova Scotia, crossed international borders and tested the new technologies that would be required on future trans-Atlantic missions. Glider RU17's first attempt at the Atlantic crossing started off the coast of New Jersey and ended in what may have been a biologically induced leak offshore the Azores and the always heartbreaking loss of a glider at sea. One year later, glider RU27, a second trans-Atlantic Slocum glider christened *Scarlet Knight* by U.S. IOOS, was launched off New Jersey. Visited by divers in the Azores for a visual inspection, it was freed of barnacles while still in the water and continued traveling its 7,400-km course. After spending 221 days at sea, it was recovered in Spanish waters by the Puertos del Estado buoy tender *Investigador,* making it the first underwater robot to cross an ocean basin. It now resides in the Smithsonian's National Museum of Natural History. What was unique about these three missions is that they were conducted with undergraduate students as part of their classroom experience, beginning in the construction phase, throughout the three ocean journeys, and into the post-mission data analysis phase, providing a unique opportunity for participatory science learning.

This manuscript provides an overview of the education programs developed, how they were applied to the trans-Atlantic missions, and the educational lessons learned. It concludes with a perspective on how this educational effort provides the foundation for an international partnership to explore the world ocean on a second NOAA challenge, a repeat of the 1870 Challenger Mission, the first scientific circumnavigation of the globe.

New Approaches to Undergraduate Education

Rising Above the Gathering Storm noted that while 30% of students entering U.S. colleges intend to major in science and engineering; less than half complete their bachelor's degrees in these subjects. Even qualified students grow discouraged before reaching the workforce. The report recommends providing undergraduate research experiences that extend beyond the classroom and across the summer as early as possible and emphasizes the need for near-peer mentorship to augment engaged faculty. Since the envisioned trans-Atlantic glider mission would require a workforce for construction, prelaunch testing, and post-launch path planning and data analysis with limited support for technician time, student participation was necessary. But how could the required long-term student involvement fit within an already busy undergraduate schedule, and how would it help the students in their future job searches?

Our approach was informed through a needs assessment process facilitated by the NSF Centers for Ocean Sciences Education Excellence-Networked Ocean World (COSEE-NOW). The needs assessment confirmed that oceanographic graduate education programs are still looking for Ph.D. students with strong basic science and math backgrounds, but it also revealed that federal agencies, companies, and even some university research laboratories are also looking for oceanographers with bachelor's and master's degrees. Other requirements include people to operate new observing technologies, to run and interpret forecast models, and to communicate scientific information. The assessment indicated that government agencies are willing to support undergraduate internships as a cost-effective way to both engage and evaluate students as potential new employees, with opportunities for earning of a master's degree once hired. Support for certification of oceanographic professionals was found to be greatest at the bachelor's degree level (Rosenfeld et al., 2009). Employers are looking for individuals with a cross-disciplinary education (oceanography plus a minor), a range of technical abilities that could adapt to different jobs, strong written and verbal communication skills, and hands-on real-world working-team experiences. An educational environment that developed the student's ability to work as part of a larger team was especially well received by companies. If a student receives a bad grade in a class, the bad grade can be hidden, since it only affects the individual. But workplace activities are often team efforts, where the failure of one team member publicly impacts the entire team. In addition, federal agencies emphasized that the desired workforce should be more diverse and more reflective of the U.S. general population. U.S. census bureau estimates for 2008 indicate that the 22-year-old resident population is 62% White, non-Hispanic. NSF graduation statistics for 2008 indicate that the existing undergraduate marine science pool is extremely small, with only 2,109 bachelor's degrees awarded nationally (Figure 1). In these marine academic disciplines, 82% of the bachelor's degrees were awarded to White, non-Hispanic students, and 59% were male.

In response to *Rising Above the Gathering Storm* and guided by the COSEE-NOW needs assessment, the NOAA trans-Atlantic glider challenge has become the catalyst for transforming our approach to undergraduate education in marine sciences. To move students beyond the marine science classroom into a team project environment and to increase diversity, an undergraduate education program was established based on the cognitive apprenticeship model restated more simply as "watch one, do one, teach one". (See education break-out box in Glenn and Schofield, 2009). The three phases start with the initial engagement, move on to team research, and culminate with veteran students in leadership roles mentoring the new students. Students from diverse disciplines across the campus are engaged as early as their freshman year, with opportunities to continue with the program through graduation. Initial engagement occurs by (a) recruiting from several traditional 100-level science-distribution Introduction to

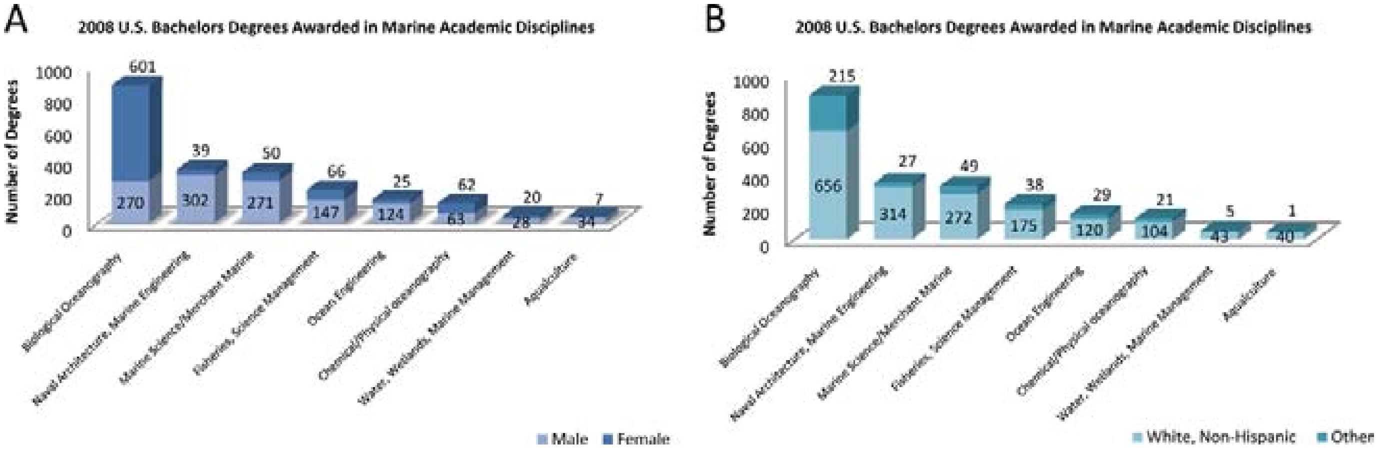


FIGURE 1

Distribution of the 2,109 U.S. bachelor's degrees awarded in marine academic disciplines for 2008 by sex (A) and ethnicity (B). Source: *National Science Foundation*.

Oceanography lecture courses, to which we have added (b) faculty participation in a university-wide series of one-credit freshman seminars where small groups of 20 students are introduced to senior level faculty, (c) the establishment of the Oceanography House as an on-campus living-and-learning community for incoming freshmen with an interest in the ocean, and (d) through near-peer university-sponsored events and an active Oceanography Club where students already involved discuss their involvement with other Rutgers undergraduates or with students back at their high schools.

At the middle level, while students are completing their usual content courses for their major/minor, a new team research track that runs in parallel with their coursework was developed. Undergraduate marine science degrees, as do several other sciences at Rutgers, require at least six credits of research to graduate. To help students fulfill this requirement, the one-credit *Atlantic Crossing* research course was established. The team-taught course runs every semester, and as a research course, students can sign up for it multiple times, potentially taking it every semester of their undergraduate career. The class typically is divided into small working teams of two to three students. Team projects initially focused on the glider rebuilds for long duration, the testing of new systems, and the development of path planning tools to understand the uncertainty associated with the constantly evolving ocean currents used as a roadmap. The product at the end of each semester is a poster session by each working team similar to those conducted at science conferences.

Finally, three capstone opportunities are offered. First, as students become more experienced, they become team leaders, responsible for organizing and reporting their team's progress and acting as a mentor to younger students. Many students have found the long-term progression from a rookie to a veteran team member an achievable goal and a confidence-building experience. Second, the glider datasets provide senior thesis topics for those who want to expand their formal research skills through the preparation and defense of an honors thesis. Often senior theses begin through summer internships available after the student's junior year. Third, the NSF-sponsored nationally coordinated course *Communicating Ocean Sciences to Informal Audiences (COSIA)* is offered for those desiring an introduction to learning theory with participatory opportunities to develop their communication and teaching skills. In *COSIA*, the gliders are a proven magnet, providing a vehicle for engaging informal audiences outside the classroom in more interactive learning activities.

The above approach—needs assessment followed by implementation of a cognitive apprenticeship learning model—can be applied to develop a wide variety of undergraduate education opportunities. It does not require a fleet of gliders to implement.

Application to the Trans-Atlantic Glider Missions

Vehicle Construction. When the trans-Atlantic challenge was issued, Rutgers had completed 66 glider missions, ¾ being in shallow shelf waters and ¼ being in the surface layers of the deep ocean. Mission durations depend on the number of sensors on board, the water depth of operations (deeper water being more power efficient), and the amount of time spent communicating. The longest mission in May of 2006 was 27 days. Since then, many deeper missions were completed with standard alkaline battery packs and only Conductivity, Temperature and Depth (CTD) sensors in the 30- to 40-day range, with a theoretical value of 34 days. A trans-Atlantic mission would require an estimated 300 days, a factor of 10 increase in mission duration. This would not only require more power but also ruggedizing mechanical systems for surviving the longer durations at sea and protection from corrosion and biofouling that do not normally plague a mission of 1-month duration.

Students worked alongside Rutgers technicians in the laboratory to adapt gliders for long-duration missions. Some of these students were on work-study plans with their pay already supported as part of their financial aid package. Others worked for hourly pay or for course credit. This phase was especially well suited for entraining engineering undergraduates. The students learned to take gliders apart, reassemble them with new test parts, reballast, and prepare them for launch. Software changes were tested on simulators. When class schedules permitted, students would accompany technicians on the launch and recovery cruises. The required factor of 10 increase in power was achieved by switching from alkaline to lithium batteries that had four times the energy, building and test flying an extended payload bay that increased the number of batteries from 230 C-cells to 453 C-cells and by reducing the daily average power usage from 2 to 1.5 W by removing the altimeter, the payload bay computer, and lowering the amount of data transferred over Iridium. Corrosion protection was monitored and evaluated by students weighing all parts before and after each deployment. A variety of paints and coatings were tested as student projects to limit biofouling.

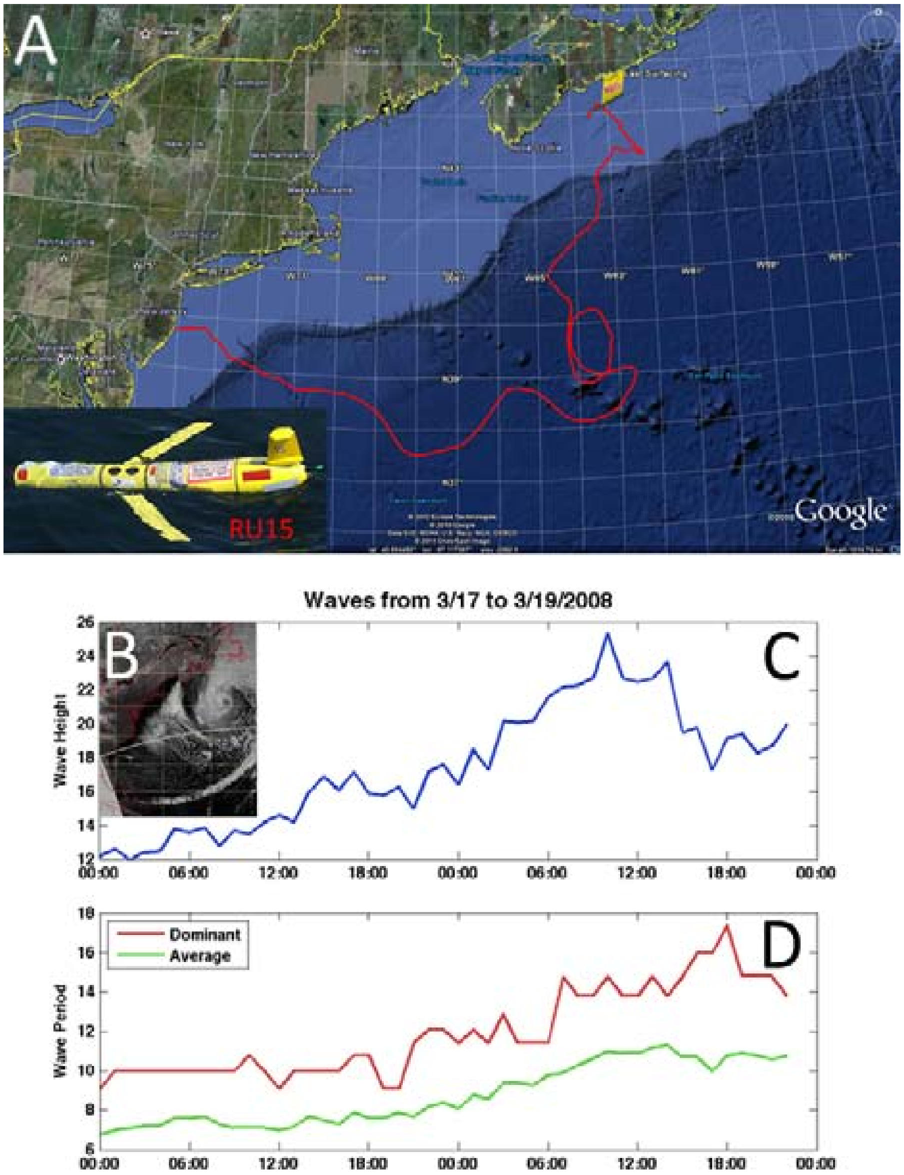
Mission Planning Tools. A flight across the Atlantic would require mission planning capabilities well beyond those available in May of 2006. Rutgers had coordinated several month-long Office of Naval Research (ONR) Coastal Predictive Skill Experiments from a collaboratory located at a remote field station (Glenn et al., 2000a, 2000b; Glenn and Schofield, 2003) and recently completed a series of NSF studies of the Hudson River plume with an on-campus collaboratory (Chant et al., 2008). But these studies were relatively short in duration compared with a trans-Atlantic mission that would require sustained operations for many months. Some of these capabilities were developed during the ONR Shallow Water 2006 Joint Experiment on the New Jersey outer shelf (Tang et al., 2007). In this experiment, a distributed team of collaborators was provided an online coordination portal where scientists posted environmental data updates that could be accessed over the Internet on shore or via HiSeasNet on board the fleet of ships. The portal provided a mission planning capability for a coordinated fleet of gliders and ships by sharing daily updates of the environmental conditions.

The trans-Atlantic glider missions required development of a similar collaborative workspace to coordinate the activities of a distributed team of scientists and students located on both sides of the Atlantic and living in different time zones. The international team would require (1) common access to the variety of datasets acquired and forecasts generated on both continents, (2) the ability to overlay the datasets and forecasts in a common operational environment to create new composite analyses for mission planning, and (3) the ability to share our analyses, results, and interpretations so flight decisions could be made. The collaborative portal also had to be constructed and operated with considerably fewer resources than were available to the Shallow Water 2006 Joint Experiment. To accomplish this, the expertise of COSEE-NOW was again tapped to establish an online learning community. The IOOS Mid-Atlantic region was chosen as our testbed, and our students became the beta testers.

To accomplish the first task above, a collaborative Web portal was designed that access points to all existing analyses products and programs could be posted and shared. Rather than build a dedicated set of software tools for overlaying the wide variety of available data and forecasts, Google Earth was chosen as our mission planning tool for the second task. Many of the required datasets (coastlines, bathymetry, weather) were already in Google Earth, and new datasets could be added relatively easily. The full capabilities provided by Google Earth were used to overlay and compare spatial maps, to zoom and pan, to pull off latitudes and longitudes, and to measure distances and bearings. Major data layers added to Google Earth include global ocean forecasts, satellite maps of sea surface height and the resulting geostrophic currents, satellite-derived sea surface temperature and ocean color maps, and the glider tracks with depth-averaged currents. Students were quick to learn the many features of Google Earth and soon developed their ability to create their own analyses and interpretations. The third piece was the ability to post the new analyses products along with an explanation in an open forum. A blog space was established using open-source software. The blog was used not only as our own mission log but also as a means to share interpretations and comment on others. Students posted their weekly assignments to the blog and used the blog to discuss their results each week in class. The blog evolved into the students' textbook, written by the professors and students themselves, and quality controlled through weekly discussions of the postings.

FIGURE 2

(A) Track for RU15 mission to Halifax, Nova Scotia, Canada. Significant wave height (C) and wave periods (D) from a nearby NOAA weather buoy during a late winter/early spring storm (B) event.



RU15—New Jersey to Nova Scotia. Glider RU15's test flight to Halifax was our first long-duration test mission. It was run on a standard size glider, one of the first equipped with the new ruggedized tailfin designed for the Navy (Figure 2). ONR needed long-term tests of the new fin, especially to determine if the shorter tail would maintain communications during storms. NOAA needed a test of lithium batteries on the coastal gliders to see if they could provide the additional energy for power hungry biological sensors. RU15, modified by Rutgers glider technicians and students to fly off of lithium batteries, was deployed on the New Jersey coast in March of 2008 (Figure 2A). It flew for nearly 2 months on a track that took it out on the Tuckerton Endurance line (Castelao et al., 2008) across the shelf and slope and into the Gulf Stream. Weekly class activities included discussions of the best locations and methodologies for crossing the heavily fished shelf break. Students learned the commands for flying deep below the fishing nets and aiming for locations between the canyons that were focal points for fishing activity. Following the Gulf Stream downstream and exiting about 62.5 W, RU15 headed for a newly formed warm core ring for a boost of momentum to the north. In the process, students were introduced to the many satellite products for locating the meandering Gulf Stream, the ring formation, propagation and absorption process, and the history of ocean forecasting that developed from this region. Exiting the ring proved difficult, requiring a second lap around rather than a slow flight against the strong head current. Scientists and students learned the value of simple path planning tools to decide where to enter a ring and when to start leaving. After exiting the warm core ring on the second lap, RU15 flew from small eddy to small

eddy across the Slope Sea, flying back up onto the continental shelf near 63 W and continuing east over the more wind-driven outer shelf until it reached the historic Halifax Line. From there, RU15 flew into shore where it was recovered by our collaborators at Satlantic, Inc., offshore Halifax Harbor. Along the way, RU15 encountered a large winter storm with significant wave heights exceeding 25 feet recorded by a nearby NOAA weather buoy (Figures 2B–2D). Even during the height of the storm, no Iridium satellite communication calls were missed by the antenna in RU15's shortened tail fin. But tests of the lithium batteries after recovery indicated that power was used faster than we expected. Our estimate of battery power available, the power draw of the vehicle, or both were in error.

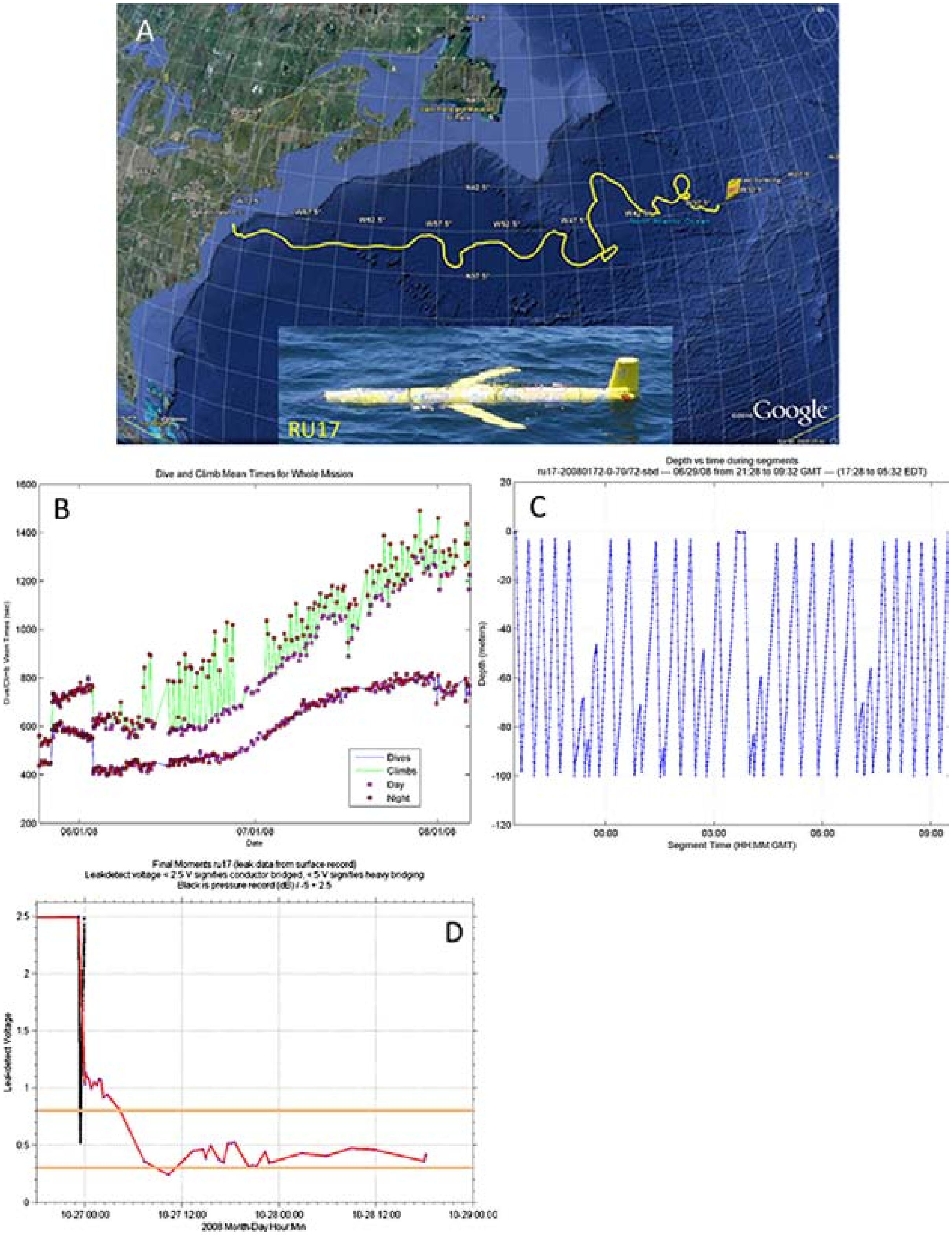
RU17—New Jersey to the Azores (almost). With RU15's recovery on April 28, work on outfitting RU17 proceeded in earnest. There was little time to deal with the power uncertainty if we were to make the spring 2008 launch window. RU17 was launched on May 21 from an offshore location on the outer shelf to save power. RU17 would follow the same general path as RU15, crossing the shelf break between seafloor canyons to avoid the fishing activity. But getting into the Gulf Stream presented problems. There were no warm core rings to catch, and RU27 was on the western side of a Gulf Stream meander crest. It was shedding shingles of warm water that RU17 had to fly against, requiring a full month to get into the Gulf Stream. But the Gulf Stream was relatively straight that spring, and RU17 quickly flew down its length past the Grand Banks of Newfoundland (Figure 3A). The first third of the mission, New Jersey to the Grand Banks, was accomplished during the spring semester with a seasoned crew of students repeating what they had just learned from the RU15 test deployment.

The next task, passed from the *Atlantic Crossing* class onto our summer student interns in the NSF Research Internships in Ocean Sciences (RIOS) program, was to cover the middle third of the mission, flying RU17 from the Grand Banks to the Azores. After passing the Grand Banks, the Gulf Stream splits and filaments, taking several routes east. The region is characterized by an energetic mesoscale eddy field, with eddies that can speed the glider's progress east or totally halt it, sending it back west. This is precisely what occurred at 45 W where RU17 encountered a strong eddy that stopped eastward progress. Summer students running simulations with virtual gliders flying through the Navy's model forecast currents determined that our only alternative was to backtrack with the current to the west, then turn north to a zone of more favorable currents much farther north. The 5° of latitude excursion, with path decisions informed through model simulations, required a full month to complete. RU17 then turned east until about 38 W. During this segment of the flight, engineering students monitoring the flight parameters noted that the biological interactions intensified. Three types of interactions were discovered. One was a behavior that slowed down the glider's vertical motion during the night, and then let it speed up again during the day (Figure 3B). A second behavior included times that the glider's upward motion would nearly or completely stop (Figure 3C). Similar behaviors had been observed in the Gulf of Mexico when negatively buoyant Remora attach to a glider and hold the vehicle down until it triggers an emergency ascent. The third behavior student engineers discovered was the spinning of the glider caused by drag on one side. Hypothesizing that something may have been snagged by one of the wings, technicians and students developed a procedure to fly backwards that they tested on simulators. By deflating the tail floatation bag, pulling the pitch battery all the way back to lower the tail as if it is ascending and simultaneously pulling the pump in to reduce the volume, the glider sinks tail first, flying backwards. Repeated attempts could not clear whatever was causing the drag, and the spinning persisted. Over time, the engineers noted that the spinning was tied to the cycle of the moon. The spinning was worse during the new moon, when the biologists suspected that bioluminescence made the glider one of the brightest objects in the region. During the full moon, the spinning would cease, and the glider was able to fly a steady course again. Given this, our plan was to conserve power and use flight time during the new moon to reach the Azores so that an observation vessel could be launched for a visit.

That plan changed suddenly on October 26, when just before midnight GMT, RU17 scrambled to the surface to report a leak. Leak detection sensors are located in the nose and the tail of each glider. If even a drop of water crosses the leak sensor, a voltage drop is detected and the glider does an emergency ascent. We had seen leak detects with small voltage drops in gliders before, and upon recovery, a failure in an O-ring was detected by visual inspection. This leak detect was different, with an immediate and

FIGURE 3

(A) Track of RU17 on the flight towards the Azores. (B) Average duration of full excursion dives (bottom line) and climbs (top line) showing the day-night variation in climb performance. (C) Sample segment showing normal climbs (100–2 m) and numerous aborted climbs during the local night. (D) Time series of leak detect voltage (red) from the time of the last dive (black dots) on October 27 until the loss of communications on October 28, 2008. Yellow bars show the range of leak detect voltages in laboratory tests for water touching the leak detect sensor (top) to full immersion (bottom).



much larger voltage drop than we had ever seen. From the engineering data, the leak detect was triggered as RU17 was ascending toward the surface at a depth of about 50 m. The large voltage drop on the leak detect indicated that this was unlikely to be a similar O-ring failure. If it was corrosion, it is expected that the hole would break open on the way down as the pressure was increasing, not on the way up as pressure was decreasing. A leak in the air bladder would also result in a significant change in the vacuum inside the pressure hull. There was no change in vacuum, and an air bladder leak would be expected to occur at the surface when the bladder is being inflated, not at depth. Moving to the front, the seams on the movable piston on the buoyancy pump are a possibility, but the design cycles had not been exceeded, and a piston leak would be expected when it is moving at the top or bottom inflection points, not in the middle of a glide. We concluded that the most likely location for a leak of this size that could not be ruled out by the engineering data would be associated with the hull fittings of the CTD. In deployments off Hawaii, we have seen the CTDs damaged by big fish, including sharks, that can bend the sensor by bumping into it, presumably while they are chasing smaller preys that use the glider for cover.

RU17 remained at the surface for 2 days, transmitting its position and engineering data. While preparations were being made for recovery, the leak detect voltage continued to drop (Figure 3D). Students measured the reaction of the leak detect sensors to different amounts of seawater in the laboratory, discovering that the leak detect voltage was already suggesting that the sensors were fully submerged in seawater. Finally, on October 28, we received the last transmission from RU17. The flight of RU17 resulted in the loss glider and heartbreak but also the accumulation of significant knowledge on the long-duration flight requirements for shallow gliders. It reminded everyone of the risk.

RU27—New Jersey to Spain. Lessons learned from the flight of RU17 were used to inform the construction a second long-duration glider with an education mission. RU27 was constructed with an extended payload bay by Teledyne Webb Research as a new product, and as with RU17, the altimeter and payload bay computer were removed. The 100-m buoyancy pump used in RU17 was replaced with a 200-m pump based on the successful repeated deployments by Oregon State University. New pin supports strengthened the CTD. The 435 lithium C-cells on RU17 grew to 453 plus 15 reserve on RU27 by space-saving rearrangements of the internal electronics (Table 1). A Coulomb meter was developed and installed to measure how much energy was being drawn from the batteries. Hull sections and the tail cone were coated with the light rubberized ClearSignal (Lobe et al., 2010) to minimize the need for heavy ablative antifouling paints. Students were involved with all aspects of the build and conducted a test flight from February 18 to March 13, 2009, across the shelfbreak to deepwater to tune the steering and establish the power usage.

RU27 was christened the *Scarlet Knight* by IOOS on March 23, 2009. Placed inside the hull was a NOAA coin, a USB memory stick containing over 100 letters from school children to be printed in Spain and sent back upon arrival, and paper copies of the letters congratulating partners on both sides of the Atlantic, just in case the mission was successful. The *Scarlet Knight* was launched offshore Tuckerton, New Jersey, on April 27, 2009, 10 years after the first Slocum glider was flown at sea in the same location by Doug Webb and a Rutgers student and 20 years after the publication of *The Slocum Mission* (Stommel, 1989).

Continuous monitoring of the flight was coordinated by professors (S. Glenn, O. Schofield, and J. Kohut) working with teams of undergraduate students in the Rutgers *Atlantic Crossing* research course during the spring and fall semesters and with teams of undergraduate interns participating in the pilot for the Summer Research Institute sponsored by the DHS Center of Excellence for Port Security between semesters. Typically, 10 teams of two to three students were working in parallel on different aspects of the mission,

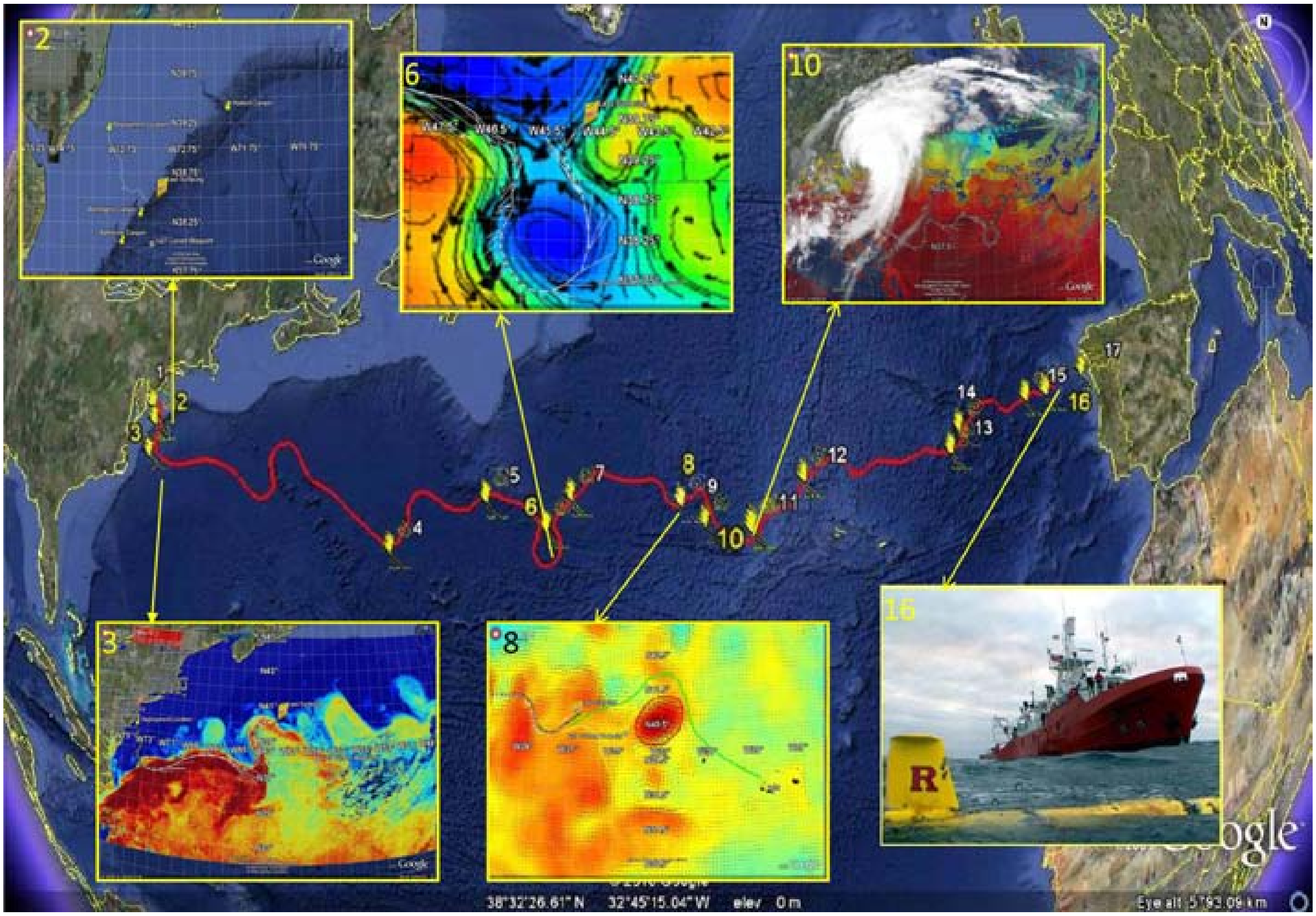
TABLE 1

Battery pack comparison for a standard alkaline-powered coastal glider and the RU27 lithium-powered trans-Atlantic glider (not including 15 batteries reserved for emergency power).

	Number of C-Cells	Energy per C-Cell	Daily Average Power Use	Theoretical Duration	Cost per C-Cell	Total Battery Cost
Alkaline Slocum	230	21.6 kJ	2 W	34 days	$5.22	$1,200
RU27	453	88.5 kJ	1.5 W	371 days	$50.60	$22,922
Factor	1.9	4.1	1.33	10.9	9.7	19.1

FIGURE 4

Trans-Atlantic track of RU27 marking the location of 16 significant events in the flight. Insets: (2) RU27 leaves the shallow water and fishing activity of the Mid-Atlantic Bight continental shelf; (3) RU27 navigates the meandering warm jet of the Gulf Stream flowing from Cape Hatteras to the Grand Banks; (6) RU27, after encountering a strong head-current, flies around the southern side of a large cyclonic cold-eddy; (8) RU27 approaches the Phantom Eddy in the HyCOM forecast, an artifact generated by the data assimilation scheme; (10) Hurricane Bill leaves the U.S. East Coast and turns east toward RU27; (16) RU27 is approached by the Spanish *R/V Investigador* for recovery (photo by diver Dan Crowell).



from watching the weather for winds and waves, validating the ocean current models, monitoring the glider flight performance and its ability to communicate, analyzing the glider data, definition of a safe landing zone, and logistics for recovery. The students blogged their results and met weekly as a group to discus new information and define strategies for the next week.

The flight track of RU27 across the Atlantic is shown in Figure 4, where the flight blog highlights labeled by number in the figure are described in Table 2. By May 2, RU27 had completed the dangerous trip across the continental shelf, where it encountered fishing fleets and shallow water without an altimeter. From there, the glider would be in deepwater, where it would remain for the rest of the mission. By May 7, RU27 had made it into the Gulf Stream. The strategy was different from before, with RU27 instead approaching an eastward propagating Gulf Stream meander from the downstream side. As the meander crest propagated forward, RU27 was entrained after only 10 days at sea and a full 10 days ahead of the projected schedule. With May being one of the historically best months for viewing satellite sea surface temperature (SST) images of the Gulf Stream, RU27 easily traversed the Gulf Stream's entire length in less than a month, with only a short delay caused by a quick encounter with a cold core ring near May 23. The first half of June was spent circling around the southern side of a large cyclonic eddy that

TABLE 2

RU27 Blog Highlights from 2009.

No.	Date	Event Description
1	Apr 27	Deployed from Tuckerton, NJ.
2	May 2	Leave the continental shelf and enter deepwater where it will remain for the entire deployment. Successfully made it through the fishing activity and did not collide with the bottom without an altimeter. First look at the deepwater power usage.
3	May 7	Into the Gulf Stream. Only 10 days at sea and already 10 days ahead of schedule.
4	May 23	Spun out of the southern side of the Gulf Stream and into a cold eddy. Turn north to fly back into the Stream.
5	Jun 5	Leave the Gulf Stream region, passing south of the Grand Banks of Newfoundland. Encounter a head current along the northern side of the largest cold eddy of the trip, requiring RU27 to loop around its southern side.
6	Jun 18	Finally pull out of the cold eddy on its eastern side, just before being swept around for a second loop.
7	Jun 29	Break through a countercurrent after a week-long struggle to fly just 125 km. This was RU27's first persistent countercurrent not associated with a strong eddy structure.
8	Jul 19	After navigating the eddy field with excellent ocean forecasts, RU27 encounters a forecast eddy that is clearly incorrect. RU27 focuses our attention on a series of sensitivity studies as to why this anticyclonic warm eddy incorrectly appears in the forecast.
9	Aug 2	Enter European waters for the first time. These are the Portuguese waters surrounding the Azores. The steering difficulties attributed to an unknown biological interaction begin.
10	Aug 25	Hurricane Bill passes to the north, generating large waves. The glider team prepares to depart the Azores on the sailboat *Nevertheless*.
11	Aug 28	Glider team completes its mission to document the biological activity on RU27, clean off the barnacles they found, and let it resume its mission without taking the glider out of the water.
12	Sep 8	RU27 breaks the along-track distance record of 5,700 km set by RU17 in 2008.
13	Oct 12	RU27 hits the half-power point on the theoretical power curve.
14	Oct 22	RU27 breaks free of the second persistent countercurrent. Like the first encounter, a full week of careful navigation was required.
15	Nov 14	RU27 crosses into European waters for the second time. This time it crosses into Spanish waters off of the Spanish mainland.
16	Dec 4	Recovery aboard the Spanish Research Vessel *Investigador*. RU27 exactly on target. Just north of the maritime border between Spain and Portugal and just west of the 12 W line, safe from the shipping traffic and fishing activity.
17	Dec 11	Landfall in Baiona, Spain

seemed to be parked just to the east of the Grand Banks. The rest of June and July was spent navigating the North Atlantic mesoscale eddy field, flying from eddy to eddy based on guidance from satellite altimeters and ocean forecast models. It was during July that RU27 focused attention on the largest forecast model error encountered on the trip, a mesoscale anticyclonic circulation that came to be known as the Phantom Eddy generated through the incorrect treatment of the combined drifter and satellite altimetry ingested by the data assimilation component of the forecast system.

In August, RU27 entered the European waters surrounding the Azores. This is where steering problems attributed to an unknown biological interaction began. At times, RU27 would fly straight, and at other times, it would spin in a tight circle, with no apparent day-night or moon phase cycling as observed for RU17. On August 25, Hurricane Bill passed to the north of RU27, leaving large waves in its wake. As Bill dissipated over the United Kingdom, a glider team left the Azores on the sailboat *Nevertheless* to document the cause of the steering problems. On August 27, the glider team rendezvoused with RU27, discovering that barnacles had attached themselves to the narrow uncoated seams between the five glider hull sections, forming four rings of barnacles that circled the glider. The barnacles could fan out or retract, creating significant and variable drag on RU27. The uneven growth resulted in uneven drag and steering offsets. The barnacles were photographically documented and then removed by hand by divers, while RU27 remained in the water.

Once cleaned and flight characteristics were verified, RU27 resumed its mission to fly east the next day on August 28. September and October continued the process of navigating the North Atlantic eddy field based on satellite altimetry and forecast model guidance. On November 14, RU27 crossed into European waters surrounding the coast of Spain and Portugal. Inspired by discussions with their student collaborators in the Azores and Canaries, the undergraduates chose Baiona, Spain, for RU27's potential landfall because of its historical significance. Baiona is the Spanish port where the caravel *Pinta,* the fastest of Columbus' three ships (the first to sight the New World and the first to return to Europe in 1493), made landfall. RU27 proceeded to the chosen pick-up point, a safe spot just north of the maritime Spanish-Portuguese border and just west of the high traffic north-south shipping lanes. It was recovered by Puertos del Estado using the *R/V Investigador* on December 4, 2009, the first underwater glider to be deployed on the western side of the Atlantic and recovered on the eastern side. The trans-Atlantic flight of RU27 required 221 days to cover the 7,400 km along-track distance, completing over 22,000 undulations and making over 1,000 satellite phone calls to report data and receive new commands. Total power used was 7,750 Wh, equivalent to a 100-W light bulb turned on for 77.5 h or just under 3.25 days.

On December 9, 2009, still aboard the recovery vessel *R/V Investigador,* RU27 made landfall in Baiona. It was here in Baiona that Spain's Minister of Development officially returned RU27 to the U.S. delegation, lead by representatives of the U.S. White House Office of Science and Technology Policy, NOAA, and Rutgers. A congratulatory video from the U.S. Secretary of Commerce was played, and the Mayor of Baiona unveiled a new RU27 plaque permanently placed on the seawall next to the plaque commemorating the voyage and crew of the *Pinta.*

Over 25 multiauthored student research posters were constructed from the flight and presented at research meetings, including one summary student poster representing the entire team that was presented at the 2010 Ocean Sciences meeting. The Dean of Undergraduate Education sponsored events for the students to tell their stories and inspire other undergraduates to get involved. Our class size doubled each semester, from 3 to 7, to 13, to 26 over the 2 years covering the flights of RU17 and RU27, leveled off near its present range of 50–60. The opportunity for undergraduate students to gain hands-on experience with the latest technology, to take risks with a robot at sea while remaining in a safe on-shore environment, and to experience the international collaborative teamwork required to successfully complete this mission are reasons cited by the students in their own recruiting video.

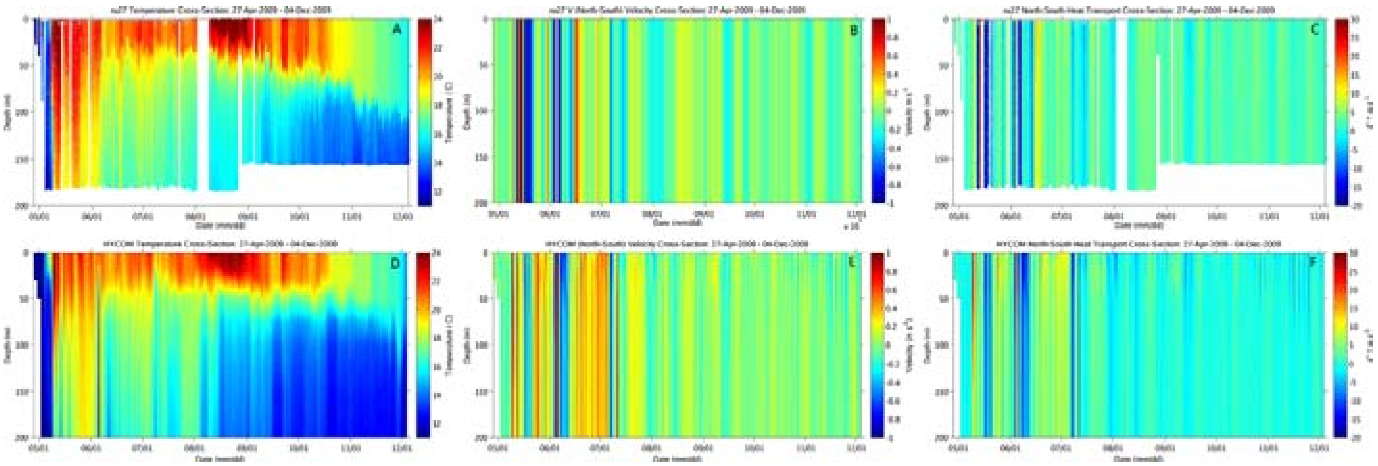
In addition to oceanography classes, the trans-Atlantic flight was used as the subject of a documentary filmed, edited, and produced by a collaborating English professor (D. Seidel) and her undergraduate students in a series of English courses, including *Documentary Filmmaking* and *Digital Storytelling*. The documentary *Atlantic Crossing: A Robot's Daring Journey* has now won eight film festival awards. English students in the class not only learned documentary film making but also learned about ocean science by working alongside oceanography undergraduates for 1.5 years. RU27 also was the inspirational centerpiece for the *Communicating Ocean Sciences* course (J. McDonnell) in the spring of 2009, using climate change as the science theme and gliders as the new enabling technology. Undergraduate designed and tested hands-on glider activities designed to demonstrate new technologies for monitoring climate change at informal education institutions are now in place at New Jersey's Liberty Science Center as a permanent docent-led activity and have also been demonstrated by students on the floor of the Smithsonian National Museum of Natural History.

RU27—Post-Flight Data Analysis. The datasets collected by RU27 were analyzed by a team of summer student interns in the 2010 NSF RIOS program. The three-person undergraduate team consisted of a physics major, a biology major, and an engineering major. The interdisciplinary team results on heat transport calculated from RU27 and compared with the Navy forecast model used in the crossing is shown in Figure 5. For RU27, temperature (Figure 5A) and the northward depth-averaged velocity (Figure 5B) were combined to provide a proxy for heat transport (Figure 5C). The same variables generated from an ocean numerical model (the Navy's Hybrid Coordinate Ocean Model, HyCOM) are plotted in Figures 5D–5F.

Starting on the Mid-Atlantic Bight shelf in late April and continuing into early May as RU27 crossed the Slope Sea, temperatures in the glider data and the model are cold, around 11°C. Currents are generally slow to the south for both glider and model. From May 7 through June 5, RU27 navigated the warm water of the Gulf Stream. The glider data indicates, as expected, that the warm water of the Gulf Stream is above 18°C in the

FIGURE 5

Comparison of measured (Glider RU27; A, B, C) and modeled (HyCOM; D, E, F) trans-Atlantic cross sections of temperature (A, D), north-south component of the current (B, E) and north-south component of the heat transport (C, F) along the track shown in Figure 4.



upper 200 m along the entire length of the Gulf Stream. Temperature differences between the model and data in this region, specifically the cold bands below 100 m, are due to imperfect forecasts of the Gulf Stream position. The banding in the north-south velocity time series is apparent in both the glider data and the model. Both have a strong band of northward velocity (red) as RU27 moves north with the Gulf Stream near 64 W, both exhibit southward velocity (blue) as RU27 travels the length of the Gulf Stream from 64 to 55 W, and both turn to positive northward velocities as RU27 turns north with the Gulf Stream on May 23 near 54 W. Small differences between the model and the data can be attributed to incorrect placement of the Gulf Stream in the model, but the general trends are reproduced. Most strikingly, the depth average current returned by RU27 is not that different in structure from the actual current profile in the model. This is important, since the resulting heat transport is dominated by the variability in the currents. In this region, the water is nearly uniformly warm in the upper 200 m, and the heat transport depends on the proper location of the Gulf Stream meander crests and troughs.

Leaving the Gulf Stream region on June 5, RU27 encounters a strong anti-cyclonic eddy on the southeast side of the Grand Banks. The warm water above 18°C is shallower than 50 m in both the glider data and the model. North-south currents in both abruptly switch from southward (blue) to northward (red) as the southern side of the cold eddy is crossed, remaining in place until mid-June when RU27 breaks free of this eddy and heads east. As in the Gulf Stream, the currents dominated heat transport in the eddy, and therefore, the location of this eddy in the forecast is critical. For the next month and a half, RU27 navigated the North Atlantic eddy field. On July 29, RU27 encounters the largest forecast error observed in the model. During this time, the warmest waters above 18°C are observed and forecast to be in the upper 40 m of the temperature field. Less variability is observed in the glider data than the model, which might indicate that the model may be overestimating the intensity of eddies and their impact on the surface layer temperature field. Currents in both the model and the data show alternating bands of ± 20 cm/s north-south currents, depending on the side of the eddy. Calculating the correct heat transport from model results becomes a challenge for placing the eddies in the proper locations. At the beginning of August, RU27 turns southeast towards Portuguese waters, and a warming trend is observed in the upper 30 m of the data and the model. This warming is abruptly halted by the passage of Hurricane Bill on August 25 and the resulting mixing in both the model and the data. Continuing east from the Azores, the process of flying eddy to eddy continues as the magnitude of the variability in the eddy currents remaining relatively constant, with only occasional currents exceeding 20 cm/s in the north or south direction. The surface layer of the ocean is observed to cool as winter approaches. Water less than 14°C rises above the 100 m depth. By December, the water column is nearly uniformly cool near 14°C. Heat transport is small compared with the western side of the basin earlier in the year.

Evolving the Undergraduate Education Experience—Lessons Learned

Traditional university marine science programs are often structured around a classical model of classroom learning in the first 2–3 years, after which a small minority of the students gain field experience by working in research laboratories and gaining prized access to research cruises. This has been an effective model for developing future Ph.D. students over the last 50 years. Given the challenges facing society today, there is a greater need for science education than only grooming future Ph.D. students. It is critical that the undergraduate experience expands ocean literacy across all of the sciences and humanities. This is especially important since the observed changes occurring throughout the world's ocean will have profound economic, cultural, and security consequences. Based on our experience, oceanography provides a level of adventure that is a vehicle to inspire students to begin and continue pursuing degrees in science and engineering. Given our positive experience of entraining undergraduates into the sciences via ocean exploration, we believe it provides a blueprint for redesigning the undergraduate education curriculum. In fact, it is now being reapplied at Rutgers with a larger and even more distributed group to engage students in environmental sciences issues associated with the Raritan River and Estuary. The Raritan Initiative utilizes Rutgers location on the banks of the Raritan River to involve students from across campuses in interdisciplinary studies that use the river and estuary as a natural laboratory. The natural environment provides motivation, and the co-location provides access. The course work includes freshman year seminars to entrain students, an interdisciplinary team taught sophomore year field course, and the support of senior thesis studies involving data from the Raritan.

The new approach has several characteristics that are important:

It is critical to engage students as early as their freshmen year in research. The Web-based nature of ocean observatories allows students to take part with ongoing experiments, which lets them live the excitement of doing research. They experience the uncertainty, adventure, and creativity required to conduct an experiment, which provides an effective counterbalance to classroom learning that often portrays science as a very linear process. Taking part in the ocean experiments, they experience the numerous stumbling blocks, such as the loss of RU17 after months of work. These hurdles, while emotionally draining, generally engage students to see the adventure through until the end. Many of the students who joined the Atlantic crossing effort of RU17 were freshmen and sophomores. The RU17 attempt, failure, engineering analysis, construction of RU27, and eventually successful Atlantic crossing was a 3-year process. For the students to experience the full adventure, they need to be engaged early in their academic career to realize the fruits of their labor. Designing strategies to entrain the students as they enter the university is critical.This realization led us to establish Oceanography House as a dedicated freshman dormitory for students interested in the oceans regardless of their major. The living and learning community is advertised during the university open house for incoming students and provides them with a direct link to marine science from their first day on campus. Undergraduates involved in the observatory work also visit their high schools to provide science talks and act as ambassadors. The students of Oceanography House meet weekly with professors and upper class students to focus ongoing scientific efforts.

Developing a near-peer community is important for expanding diversity. A critical component to the oceanography living learning community is that incoming students are provided guidance by upper class advanced oceanography students. These oceanography mentors provide assistance in transitioning the freshmen into the ocean exploration classes. This is critical as the students entering the classes as freshmen have a wide range of expertise, represent a wide range of disciplinary interests spanning from oceanography to English, and mirror the ethnic and cultural diversity of the Rutgers student body, one of the most diverse research universities in the U.S. For the upperclassmen, they are put in a position of mentorship that requires them to understand key concepts with sufficient detail to keep the new students on track, providing teaching experience. Many of the students who do not pursue graduate school often become science teachers. This is particularly important since there is a critical need to improve science education at the K-12 education level. To assist in this process, the students are provided the *COSIA* opportunity for developing the skills required to be an inspirational science teacher by providing a firm foundation in communication techniques and pedagogy.

Allow the students to work as teams. Given the goal of increasing the diversity of disciplines, the teacher is often confronted with a wide range of student skills/science knowledge. To help address these gaps and to facilitate the near-peer relationships, student are often given specific projects as a team of three to four students. The team consists of at least one advanced upperclassmen. Teams are coordinated in a systems engineering model, where initially individual projects are iterated over a period for a few months and then the individual parts are combined to provide an overall system to help coordinate glider activities. For example, during the RU27 journey, the undergraduate teams focused on a successful recovery off the coast of Spain. The teams documented the major shipping lanes, provided weather and wave forecasts, provided logistical planning for the ship crew, and researched the history of the Spanish port cities to help a develop a RU27 recovery plan.

Give students intuitive tools to analyze data and make their own discoveries. The analysis of the RU27 data and comparisons to ocean forecasts by undergraduate summer interns was enabled by a new toolkit of interactive glider software developed specifically for education. As students gain experience with program languages and complex file formats, they could do these same analyses on their own. But developing a working knowledge of these software skills is a barrier to many students. Simple intuitive interfaces, such as Google Earth, were used by students at any level to visualize and compare datasets, allowing them to draw their own conclusions. The glider data analysis interfaces developed here and tested by the undergraduates in the 2010 NSF RIOS program enabled the students to visualize and interpret vertical glider data as easily as they did with the horizontal data in Google Earth. The result of the software test was three research posters, one on the heat transport of RU27 discussed above, a second on the flight characteristics of a new Slocum Thermal Glider, and a third on optimizing the flight profiles for heat transport calculations along 26.5 N, a standard trans-Atlantic sampling line for monitoring the maximum in the north-south heat transport caused by the Meridional Overturning Circulation.

A Future Vision—The Challenger Mission and a Global Classroom

In Baiona, Spain, Rick Spinrad reflected on his initial 2006 challenge to modify one of our gliders and fly it across the Atlantic. With this challenge complete, Dr. Spinrad issued a second challenge, to send an internationally coordinated fleet of gliders on a circumnavigation that revisited the track of the HMS *Challenger*. The original *Challenger* mission (Cornfield, 2003) was the first dedicated scientific circumnavigation of the globe. It took 3.5 years, leaving England in December 1872, returning in May 1876, and traversing 111,000 km, exactly 15 times the distance covered by RU27.

As with the trans-Atlantic glider mission, a circumnavigation will require the development of new technologies, and it will require the development of new international teams. The range of technologies potentially includes not only the full suite of electric gliders available to the international community from both the U.S. and China but also the Slocum Thermal Glider, part of the original vision of Doug Webb and Hank Stommel. The fleet will likely include a mix of gliders or even hybrids of the thermal and lithium battery technology. Our own experience has shown that flexibility in glider design is again a desired trait. Thermal gliders work best when there is a large temperature difference between the surface and the bottom of the undulation, typically about 15°C. Winter and summer forecasts from the HyCOM model indicate that thermal gliders can be tuned to cover much of the subtropical ocean basins and the tropics. Our own student calculations have demonstrated that in some cases, for example, the calculation of heat transport in the subtropical ocean basins, that flying to the deepest allowable depth on every undulation may not be the optimal dive profile. Again, flexibility in the mix of dive profiles is going to be desired, with deep profiles interspersed with shallow.

As with the trans-Atlantic mission, the Challenger Mission will require new technologies, but it will also require people. We have found that many of those people already exist—they are already in our classrooms. Our students have already developed a prospectus and approach for the Challenger Mission, starting with an expansion from the North Atlantic to the South Atlantic, followed by a circling of the globe. Moving to the South Atlantic and eventually the globe will require a transformation from a Rutgers classroom to a globally distributed classroom, facilitated by on-line virtual learning communities, entraining an even more diverse range of partners and disciplines, and providing an even broader global perspective to the generation that must deal with climate change over their lifetimes. We hope that the perspectives gained through the local *Atlantic Crossing* course and the envisioned global *Challenger Mission* course will provide our students with the scientific perspective and the global cultural experience to meet the challenges of their generation.

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Slocum gliders were developed through the vision and support of the Office of Naval Research, transitioning from an engineering demonstration on its first deployment at sea, to a research tool used by many federal agencies, to an operational Naval asset in less than a decade. NOAA provided the challenge for the first trans-Atlantic missions. Rutgers alumni, Teledyne Webb Research, NOAA, and U.S. IOOS provided support for the build and the launch. Educational support was provided by the National Science Foundation and the Department of Homeland Security. Our partners in Spain at Puertos del Estado and Universidad de Las Palmas de Gran Canaria provided support for the recovery. These and future missions would not be possible without the direct participation and continuing interest of the *Atlantic Crossing* students and their international collaborators.

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References

Castelao, R., Glenn, S., Schofield, O., Chant, R., Wilkin, J., & Kohut, J. 2008. Seasonal evolution of hydrographic fields in the central Middle Atlantic Bight from glider observations. Geophys Res Lett. 35, L03617, doi: 10.1029/2007GL032335.

Chant, R.J., Wilkin, J., Weifeng, Z., Choi, B., Hunter, E., Castelao, R., … Moline, M.A. 2008. Dispersal of the Hudson River Plume on the New York Bight. Oceanography. 21(4):149-162.

Committee on Prospering in the Global Economy of the 21st Century and Committee on Science, Engineering, and Public Policy. 2007. Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. Washington, DC: National Academies Press. 592 pp.

Cornfield, R. 2003. The Silent Landscape: The Scientific Voyage of the HMS Challenger. Washington, DC: The Joseph Henry Press. 285pp.

Davis, R.E., Eriksen, C.E., & Jones, C.P. 2003. Technology and applications of autonomous underwater vehicles. In: Autonomous Buoyancy Driven Underwater Gliders, ed. Griffiths, G., 37-58. London: Taylor & Francis.

Glenn, S.M., Dickey, T.D., Parker, B., & Boicourt, W. 2000a. Long-term real-time coastal ocean observation networks. Oceanography. 13:24-34.

Glenn, S.M., Boicourt, W., Parker, B., & Dickey, T.D. 2000b. Operational observation networks for ports, a large estuary and an open shelf. Oceanography. 13:12-23.

Glenn, S.M., & Schofield, O. 2003. Observing the oceans from the COOL room: our history, experience, and opinions. Oceanography. 16(4):37-52.

Glenn, S., & Schofield, O. 2009. Growing a distributed ocean observatory: our view from the COOL room. Oceanogr Mag. 22(2):128-145.

Lobe, H., Haldeman, C., & Glenn, S. 2010. ClearSignal coating controls biofouling on Rutgers glider crossing. Sea Technol. 51:91-96.

Munk, W. 2000. Oceanography before, and after, the advent of satellites. Elsevier Oceanogr Ser. 63:1-4. doi: 10.1016/S0422-9894(00)80002-1.

Rosenfeld, L., Sullivan, D., & Murphree, T. 2009. Certification for oceanographic professionals: a needs assessment study. The MATE Center. 1-72 pp.

Schofield, O., Kohut, J., Aragon, D., Creed, L., Graver, J., Haldeman, C., … Glenn, S.M. 2007. Slocum gliders: robust and ready. J Field Robotics. 24(6):1-14. doi: 10:1009/rob.20200.

Schofield, O., Kohut, J., Glenn, S., Morell, J., Corredor, J., Orcutt, J., … Boicourt, W. 2010a. A regional Slocum glider network in the Mid-Atlantic bight leverages broad community engagement. Mar Technol Soc. 44(6): 185-195.

Schofield, O., Glenn, S., Orcutt, J., Arrott, M., Brown, W., Signell, R., … Oliver, M. 2010b. Automated sensor networks to advance ocean science. Trans Am Geophys Union. 91(39):345-346. doi: 10.1029/2010EO390001.

Stommel, H. 1989. The Slocum mission. Oceanography. 2(1):22-25.

Tang, D., Moum, J., Lynch, J.F., Abbott, P., Chapman, R., Dahl, P.H., … Newhall, A.E. 2007. Shallow Water '06—A joint acoustic propagation/nonlinear internal wave physics experiment. Oceanography. 20(4):156-167.