**The Trans-Atlantic Slocum Glider Expeditions:**

**A Catalyst for Undergraduate Participation in Ocean Science and Technology**

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**Abstract**

In 2006, after a series of successful ONR and NSF collaborative scientific research experiments using Slocum underwater gliders in the Middle Atlantic Bight, NOAA provided a Trans-Atlantic Challenge to modify one of our coastal gliders and fly it across the Atlantic, entraining students along the way. It required 3 years and 2 attempts to meet this challenge. With education as the motivation for funding, Slocum gliders were modified to accommodate a 10-fold increase in power, collaborative interfaces where constructed for mission planning, and undergraduate students were entrained as the backbone workforce. Three long-duration missions were conducted, RU15’s flight to Halifax to test the technology, RU17’s first attempt at the crossing that provided the lessons learned, and RU27’s successful flight a year later. RU27 provided a real-time focus that validated the performance but also identified problems in the data assimilation schemes of modern ocean forecast models. Its collaborative success has inspired similar Trans-Atlantic test missions with the new Slocum Thermal Glider to support climate change studies of heat transport. Biofouling remains a technology issue for the future, since many of the motivations for glider flights are focused on the upper ocean where the heat transport and the biological activity is greatest. The mission planning tools developed for the Trans-Atlantic missions are now being applied to glider mission planning in the Gulf of Mexico in response to the oil spill. The success has inspired an even broader vision, that of a glider-based global mission to repeat the track of the HMS Challenger and its first scientific circumnavigation of the globe.

**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 the world’s oceans. One vision from 21 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. 2005, 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, gliders are becoming a significant component of the NOAA-led U.S. Integrated Ocean Observing System (IOOS), the NSF Ocean Observing Initiative (OOI), the Navy’s Littoral Battlespace Sensing - Glider (LBS-G), and the coordinated national IOOS response to the Gulf of Mexico Oil Spill (Schofield et al., this issue),

This ocean omnipresence enabled by satellites, drifting profilers and gliders not only offers researchers new opportunities for ocean science, it also provides a potential mechanism to share the real-time excitement of exploration with students and the public. This opportunity was recognized by NOAA leadership in 2006 at a EU/US sponsored conference in Lithuania on scientific collaboration in the Baltic Sea. It was presented as a challenge to conduct high-risk ocean expeditions using gliders that directly involved undergraduate students in the mission so the students can experience the many difficulties of operating at sea, the value of perseverance, and ultimately the excitement of discovery in engineering and science. This challenge resulted in Rutgers and their international partners conducting three trans-Atlantic missions since 2008. RU17’s first attempt at the crossing started off the coast of New Jersey and ended in what may have been a shark attack offshore the Azores. One year later, RU27, a second trans-Atlantic Slocum glider christened *Scarlet Knight* by U.S. IOOS, was launched off New Jersey. After traveling 7,400 km and spending 221 days at sea, RU27 was recovered in Spanish waters by the Puertos del Estado buoy tender the R/V *Investigador*, making it the first underwater robot to cross an ocean basin. This success has been followed with a 2010 attempt to pilot a Slocum thermal glider named after the explorer James Cook on a trans-Atlantic mission across the middle of the North Atlantic gyre. What was unique about these missions is that they were coordinated and conducted with undergraduate students beginning in the construction phase and throughout the ocean journey, providing a unique opportunity for hands-on participation and learning.

This manuscript will provide an overview of the technical, science, and education lessons learned with these trans-Atlantic missions. We will also provide our perspective on how these missions provide the foundation for an international partnership to explore the world ocean on a second NOAA challenge, a repeat of the 1870’s Challenger Mission, the first scientific circumnavigation of the globe.

**Mission Preparation**

With the Trans-Atlantic Challenge issued in May of 2006, Rutgers scientists began the process of fund raising for a customized glider that would need to be built, modified, tested and then flown across the Atlantic. Coordinating the flight would require path planning procedures based on the best available maps of the current field, and the project would require human support from a wide range of individuals given the length of the proposed journey and the variety of tasks. The scientists quickly discovered that standard federal funding sources where not going to fund a risky attempt to fly a glider across an ocean basin as this mission did not fit into the standard technology development or scientific research cycles available at the time; therefore we turned to education funding as this was the opportunity for undergraduate students to gain hands on experience with the latest technology, take risks with a robot at sea while remaining in a safe on-shore environment, and experience the international collaborative teamwork required to successfully complete this mission. The project resonated with Rutgers alumni, who provided the funds for the glider purchase and the first set of lithium batteries. Construction of RU17, the first Slocum glider to attempt a Trans-Atlantic crossing, began at Teledyne Webb Research in early 2007.

***Advances in Glider Technology.*** When the Trans-Atlantic Challenge was issued, we 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. Our longest mission in May of 2006 was 27 days. Since then we completed many deeper CTD-only missions with standard Alkaline battery packs in the 30-40 day range, with a theoretical value of 34 days. A Trans-Atlantic Mission would require around 300 days, a factor of 10 increase in mission duration. This would not only require more power, but would require ruggedizing mechanical systems for surviving the longer durations at sea, and protection from corrosion and bio-fouling that do not normally plague a mission of 1 month duration.

*Power.* The required factor of 10 increase in power was achieved in three steps. First the batteries where changed from the standard Duracell Alkaline primary C-Cell batteries normally used on Slocum coastal gliders to the more powerful Lithium primary batteries manufactured by ElectroChem. The ElectroChem C-cells have about 4 times the power of the equivalent size Alkalines, but are approximately 10 times more expensive.

Close to a factor of 2 improvement was achieved by increasing the number of batteries on board from 230 C-Cells to 450 C-cells. This was achieved by doubling the length of the payload bay from 9 3/8 inches to 18 ¾ inches (Figure 1). The extended payload bay was specifically designed as a simple modular change accomplished by replacing the shorter center payload bay hull section with the same size hull sections used for the fore and aft portions of the glider’s pressure hull. The change required substitution of a longer wiring harness for the cables running between the hull sections, a longer through-hull bolt that runs the length of the sealed glider, and longer wing rails for attaching the wings to the center payload bay.

The third change was to reduce the power usage as much as possible in the final glider by removing any systems not completely necessary for this mission. Since we would be flying in deep water for almost the entire mission, the altimeter was removed. Since the only environmental sensor would be a CTD, the on-board science processing would be minimal. The science payload bay computer was removed and all CTD processing was switched to the glider control computer. The next major power savings was achieved by minimizing the communication time. Each communication attempt has a minimum amount of overhead associated with surfacing, gathering a GPS location, and initiating an Iridium satellite call. To reduce this overhead, we reduced the number of surfacings per day by lengthening the underwater segments. Instead of 1 hour or 3 hour surfacing intervals, we initially choose 6 hour segments and then transitioned to 8 hour surfacing intervals, reducing the number of surfacings first to 4 and then to 3 per day. We reduced the size of the data file transferred. We typically transfer about 100 kb of data for every 3 hour underwater segment. During the long durations flights, we transferred only 30 kb of data for every 8 hour segment. This reduced the transfer times for the navigation, glider status and environmental data during each surfacing. The end result of all these energy saving activities was a factor of 1.33 savings in power for RU27 (daily average of 1.5 Watts) over that of a regular coastal glider (daily average of 2 Watts).

The combined effect of using an increased number of Lithium batteries was a factor of 4.1 \* 1.9 = 7.8 increase in available power. This was combined with a factor of 1.33 decrease in power usage. The result is a factor of 10.4 increase in endurance. The theoretical endurance of 34 days for a standard coastal glider was thereby extended to a theoretical endurance of over 350 days.

*Hardening.* Before sending a glider out on a long duration mission from which there is little chance of recovery over most of its duration, there is a natural reluctance to substitute any untried hardware or software into the system. A significant concern for a long-duration Slocum flight, however, was the perceived vulnerability of the combined steering and communication system. The standard mechanism at the time was a fin located at the end of an 18 inch post that was separated from the fin and the communications antennas from the control motor. The control rod could be bent and jam, the communications antenna could be shattered, or the fin could be pulled off its rubber hinges by prolonged rough handling. The new Slocum glider Digifin was just becoming available as part of the ONR-sponsored glider hardening strategy for the Navy’s LBS-G (Figure 1). The new Digifin is made of a shatterproof plastic, is self-contained with the control motor and fin in the same location, and has a ball pin joint for resetting the zero in case the fin gets bumped while at sea. The Digifin was also smaller, therefore its ability to maintain communications in rough weather was untested. The second mechanical change was to solder or glue all connections. Internally this would ensure that all electrical connections did not shake loose from prolonged exposure to heavy seas. Externally this meant permanently attaching the wings to the wing rails so that the normal quick-release clips similarly would not shake loose. The wings could still be removed, but required unscrewing the full wing rail assembly from the attachment points to the extended glider payload bay - something to avoid at sea.

*Corrosion and Biofouling Protection.* Corrosion protection was achieved by ensuring that all metal parts were electrically connected to the sacrificial zinc anodes located inside the aft wet section of the vehicle. In some cases, electrical jumpers where attached between subsystem assemblies. The typical operational range of buoyancy change by the Slocum gliders are about 440 grams. Based on past experience with corrosion over month long deployments, it was expected that a mass of less than 10% of the buoyancy range would be lost from the zinc anodes over an envisioned 300 day deployment.

Biofouling comes in many forms and is more difficult to protect against. In the most major events in the past, fish, specifically Remoras, have attached to gliders and held them below the surface until the glider ejected its emergency ascent weight. Algae can grow on the glider and coat optical sensor windows or clog flow through sensor passageways. Barnacles can attach, causing drag on an otherwise highly streamlined shape. Anti-biofouling paint is heavy and slowly ablates over time, changing the buoyancy over a long deployment. To avoid using this paint on the main surfaces of the gliders, the 3 hull sections and the aft tail cone were coated with ClearSignal (Severn Marine Technologies & Mid-Mountain Technologies), an offshore oil industry standard for a clear, nontoxic rubberized coating that resists biofouling through its nonstick properties (see Lobe et al., 2010). The few remaining exposed metal surfaces were coated with a standard marine anti-fouling paint from E-Paint. Painting the exposed metal surfaces was also expected to further reduce corrosion beyond our standard coastal gliders.

***Advances in Collaborative Mission Planning Capabilities***. A flight across the Atlantic would require mission planning capabilities well beyond those available in May of 2006. We had operated several month-long ONR Coastal Predictive Skill experiments from a collaboratory located at a remote field station (Glenn et al., 2000; Glenn and Schofield, 2004) and recently completed a series of NSF studies of the Hudson River plume with an on-campus collaboratory (Chant et al., 2007). But both of these studies where relatively short duration, measured in a few weeks. A Trans-Atlantic Mission would require planning tools that could be operated and sustained 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. 2008). In this experiment, a distributed team of collaborators was provided an online coordination portal that could be accessed over the Internet from shore or via HiSeas net from ship. At Rutgers, we developed the mission planning tools for coordinating a fleet of gliders and providing daily updates of the environmental conditions that we used to coordinate the glider fleet. The ability to produce your own data products locally from any location with a WiFi connection was critical for the success of the coordination activities. The difficulties arose in our inability to easily overlay datasets acquired from difference sources, and the need for multiple layers of people to assemble and post new data products to be shared among participating scientists. With significantly fewer resources for the Trans-Atlantic missions, a more efficient methodology would be required.

To accomplish these missions, collaborations would be required between a distributed team located on both sides of the Atlantic. 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 with our distributed team of partners. To accomplish the first task, we designed a collaborative web portal where access points to all existing analyses products and programs could be posted and shared. Rather than build our own set of software tools for overlaying the wide variety of available data and forecasts, we chose to use Google Earth as our mission planning tool for the second task. Many of the required datasets where already in Google Earth, and new datasets could be added with much less effort than that required to develop yet another dedicated path planning tool. The full capabilities to overlay and compare spatial maps, to zoom and pan, to pull off latitudes and longitudes, to measure distances and bearings, etc., was all provided by Google Earth once the new data was inserted. Major data layers added to Google Earth include global ocean forecasts (NCOM, NLOM, HyCOM), 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. The third piece was the ability to post the new analyses products along with an explanation in an open forum blog. The blog was used as our own mission log, but also as a means to share interpretations and comment on others. The blog became a textbook for students beyond our undergraduate classroom as the oceanographic concepts, and their relation to the glider mission, were discussed.

The three collaborative tools developed for this undergraduate education project found immediate application in all of our glider activities. The educational tools were first applied in a semi-operational setting to the Mid-Atlantic Bight as part of our IOOS Mid-Atlantic Regional Coastal Ocean Observing System (MARCOOS). MARCOOS includes over 35 Co-PI’s from 22 institutions distributed around throughout the Mid-Atlantic. The specific application was to coordinate regional glider missions with NOAA fisheries surveys. The next application was to help coordinate the IOOS response to the Deepwater Horizon Oil Spill in the Gulf of Mexico (Figure 2). The website was specifically targeted at the glider deployments conducted by iRobot, the Navy, SIO/WHOI, University of South Florida, Mote Marine Lab and Rutgers. The Deepwater Horizon web portal (Figure 2A) was used to introduce the purpose of the site, included a real time map of the tracks of the gliders and the location of the oil spill, links to all the raw products produced by others, and links to the Google Earth kml files so anyone could download them and produce their own planning products. The Google Earth interface (Figure 2B) displays only a small portion of the data available, in this case an ocean model forecast, HF radar surface currents, glider tracks, buoy tracks, and the track of Tropical Storm Bonnie. Bonnie did not pass over the Loop Current Eddy that recently formed, and remained weak as it propagated northwest across the cooler waters of the Gulf and into Louisiana. The interactive Deepwater Horizon Blog (Figure 2C) shows the typical types of analyses generated, one focused on the vertical sections of data acquired by the gliders, and another focused on the horizontal maps produced by the composite analyses. The application to the Gulf of Mexico oil spill demonstrates the broader impact of education on research and applications. Because the collaborative interfaces were developed and refined during the 2008-2009 missions of RU15, RU17 and RU27, the tools could be quickly repurposed to serve research and societal needs in an emergency response to an unexpected environmental disaster.

***Advances in Undergraduate Involvement.*** The Rutgers response to NOAA’s Trans-Atlantic Challenge was primarily an education mission, with our prime goal being to entrain students in oceanographic related careers. In fact, student involvement was necessary, since technician time was minimal or non-existent. The envisioned Trans-Atlantic missions would require human involvement from prelaunch testing through post-launch path planning. But at what level would the students be involved?

The approach was informed through an informal needs assessment process facilitated by our 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, and applications to our own graduate program were growing well beyond the number of Ph.D. students we could support. But we also discovered that federal agencies and industry are also looking for oceanographers with Bachelors and Masters degrees, not just Ph.D. researchers. We found an interest in supporting undergraduate internships as a cost effective way to both engage and vet students as potential new employees, with opportunities for on-the-job earning of Masters degrees. Support for certification of Oceanographic professionals was found to be greatest at the Bachelors degree level (Rosenfeld, et al, 2009). Desired characteristics included a cross-disciplinary education (oceanography plus something else), 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 emphasis on the ability to work as part of a larger team is being especially well received by industry. If a student receives a bad grade in a class, the bad grade can be hidden, since it only affects the student. In many work situations, projects are often team efforts, where the failure of one team member publicly impacts the entire team. Federal agencies emphasized that the desired workforce also would 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 of 4,222,000 is 62% white, non-Hispanic. NSF statistics indicate that the existing annual undergraduate pool is extremely small, with only 2,109 Bachelors degrees awarded nationally in marine academic disciplines in 2008 (Figure 3). In 2008, 82% of these Bachelors degrees where awarded to white, non-Hispanic students, and 59% where male.

The Trans-Atlantic Glider Challenge has become a catalyst for changing our approach to undergraduate teaching in response to our COSEE-NOW needs assessment. To move our students beyond the marine science classroom into a team project environment, and to increase our diversity, we established an undergraduate education program at Rutgers based on the cognitive apprenticeship model of “watch one, do one, teach one”. (See education break-out box in Glenn and Schofield, 2009). We have established three phases, starting with the initial engagement, moving on to team research, and finally culminating with a leadership role. Students from more diverse disciplines across campus are engaged as early as their freshman year, with opportunities to continue with the program through graduation. Initial engagement occurs through (a) faculty participation in a university-wide series of 1-credit freshman seminars where small groups of 20 students are introduced to senior level faculty, (b) recruiting through several 100-level science-distribution introduction to oceanography lecture courses, and (c) through near-peer undergraduate education sponsored events where students already involved discuss their projects with other Rutgers undergraduates or with students back at their high schools. Then, while students are completing their usual courses for their major, we established a new team research track that runs in parallel with their coursework. Undergraduate Marine Science degrees, as do several other sciences at Rutgers, require at least 6 credits of research. To help students fulfill this requirement, a 1-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 2-3 students. Team projects initially focused on the glider rebuild for Lithium batteries, the testing of new systems, and the development of path planning tools to understand the uncertainty associated with the constantly evolving ocean currents being used as our roadmap. The product at the end of each semester is a poster presentation by each working team similar to those conducted at science conferences. Finally we offer three capstone opportunities. As students become more experienced, the 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 memorable experience in their undergraduate career. The glider datasets also provide senior thesis topics for those who want to expand their formal research skills through the preparation and defense of an honors thesis. We also teach the NSF-sponsored nationally-coordinated course, *Communicating Ocean Sciences to Informal Audiences (COSIA)* for those desiring an introduction to learning theory with hands-on opportunities to develop their communication and teaching skills. The gliders are especially exciting for audiences outside the classroom. ,

**Sea Trials – RU15 & RU17**

***RU17 Coastal Test Flights.*** Our first glider built specifically for an education program was RU17. It was delivered to Rutgers from Teledyne Webb Research not by standard shipping but by deploying it offshore Massachusetts by our IOOS partner U.Mass Dartmouth, and flown south to New Jersey along our standard ONR sampling line in May 2007, just 1 year after the challenge was issued (Figure 1a). This full scale test flight demonstrated the standard glider configuration was working. RU17 was then outfitted with an extended payload bay constructed from one of the spare fore/aft hull sections. The second flight test in July of 2007 was two laps around the Tuckerton Endurance Line (Casteleo et al. 2008a,b), proving that RU17 could be efficiently flown in its new external configuration. The next step was to rebuild the internal electronics in the planned form that would save power and provide more space for batteries (see above). RU17 was deployed in December of 2007 in its power-saving Trans-Atlantic configuration. It flew to the outer shelf were it patrolled in deepwater for 6 weeks, flying back in for recovery at the end of January.

***RU15 – New Jersey to Halifax****.* The testing for the batteries began with a standard glider, RU15. It was one of our first gliders equipped with the ruggedized DigiFin. ONR needed long term tests of the DigiFin, especially in storms, for their glider hardening work. NOAA needed a test of Lithium batteries on the coastal gliders to see if they could be used to provide more energy for power hungry biological sensors. RU15, with Lithium batteries, was deployed in March of 2008 (Figure 1b). It flew for nearly 2 months on a track that took it out on the Tuckerton Endurance line, across the shelf and slope, and into the Gulf Stream. On this portion of the track we practiced navigating across the shelf break, flying deep and aiming for locations between the canyons to avoid fishing activity. Following the Gulf Stream downstream, we exiting about 62.5 W, heading for a newly formed warm core ring for a boost of momentum to the north. Exiting the ring proved difficult, requiring a second lap around rather than a slow flight against the strong head current. After exiting the Warm Core Ring, RU15 flew from small eddy to small eddy across the Slope Sea, flying back up onto the continental shelf near 63W. RU15 then flew east over the outer shelf until it reached the Halifax Line. From there, RU15 flew into shore along the standard Halifax Line 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 (Figure 4). Even during the height of the storm, no Iridium satellite communication calls where missed by the short antenna in RU15’s new Digifin. But tests of the Lithium batteries after the flight indicated that power was used faster than we expected. Either our estimate of battery power available or the power draw of the vehicle, or both, were in error.

***RU17 - Launch and Loss.***  With RU15’s recovery on April 28, work on outfitting RU17 proceeded. There was little time to deal with the power uncertainty if we were to make the spring 2008 launch window. After preparations similar to RU15, RU17 was launched on May 21, from an offshore location on the outer shelf. In shallow water, gliders use much more power to fly a given distance because the buoyancy pump, the most power hungry device on the glider, must be moved more often. Compounding this, without an altimeter, RU17 had to stay a safe distance away from the bottom based on its pressure sensor only, further reducing the flyable depth range and further increasing the use of the buoyancy pump. RU17 would follow the same general path as RU15, crossing the shelf break between sea floor canyons to avoid the fishing activity. Getting into the Gulf Stream presented problems. There were no warm core rings to catch, and we were on the western side of a Gulf Stream meander crest. It was shedding shingles of warm water that RU17 had to fly against. It took a full month to get into the Gulf Stream. But the Gulf Stream was relative straight that Spring, and we quickly flew down its length past the Grand Banks of Newfoundland.

After passing the Grand Banks, the Gulf Stream splits and filaments, taking several routes east. At 45 W, RU17 encountered a strong eddy that stopped our eastward progress. Our only alternative was to backtrack with the current to the west, then turn north to a zone of more favorable currents farther north. The 5 degree of latitude excursion required a full month to complete. RU17 then turned east until about 38 W. During this segment of the flight, biological interactions intensified. There were two types interactions. One was a behavior that slowed us down during the night and let us speed up again during the day. The day night variation was discovered by the undergraduates working on this flight (Figure 5a). A second behavior included times that the gliders upward motion would nearly or completely stop (Figure 5b). Similar behaviors have been observed in the Gulf of Mexico when negatively buoyant Remora attached to the gliders and hold the vehicle down until it triggers an emergency ascent. The third behavior was the spinning of the glider caused by drag on one side. It was thought that something may have been snagged by one of the wings. To try to clear any item snagged on the wings we developed a flight strategy to fly backwards. 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 we noted that the spinning was tied to the cycle of the moon. The spinning was worse during the new moon, when we suspected that bioluminescence made us one of the brightest objects in the region. During the full moon, the spinning would cease, and we were able to fly a course again. Given this, our plan was to conserve power, and use flight time during the new moon to reach the Azores so we could launch an observation vessel.

That plan changed suddenly on October 26, when just before midnight GMT, RU17 scrambled to the surface to report a leak (Figure 5c). 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, pulling its batteries all the way back, pushing out any remaining water in the nose, and heading to the surface as fast as possible. We had seen leak detects in gliders before, where the voltage drop was small and the glider surfaced. Upon recovery, on one occasion after weeks of remaining at sea waiting for a recovery vessel, several drops of water were found and a failure in an O-ring was detected by visual inspection. This leak detect was different, with an immediate and much larger voltage drop than we have ever seen. Downloading the engineering data, we saw that the leak detect was triggered as RU17 was ascending toward the surface at a depth of about 50 m (Figure 5c). The large voltage drop on the leak detect indicated that this was unlikely to be a similar O-ring failure. If it was corrosion that caused a hole to develop, we would have expected the hole to 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 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, an 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 prey that use the glider for cover.

RU17 remained at the surface for 2 days, transmitting its position and engineering data. While preparations where being made to fly to the Azores, the leak detect voltage continued to drop (Figure 5d). Finally, on October 28, we received the last transmission from RU17. The flight of RU17 resulted in the loss glider, heartbreak, but the accumulation of significant knowledge on the long-duration flights of Slocum gliders. It reminded us all of the risk.

**Trans-Atlantic Flight of RU27**

Immediately after the loss of RU17, construction of a second educational Trans-Atlantic glider was commissioned. The Rutgers alumni contribution was matched by Teledyne Webb Research for the purpose of education. Several modifications to the design where made. RU17 was a shallow Slocum glider with a maximum depth rating of 200 m. Despite being flown in deep water, RU17 was equipped with a 100 m buoyancy pump because of the proven reliability of 100 m pumps on the NJ Shelf. Oregon State University had now demonstrated a similar successful field record with 200 m buoyancy pumps. Laboratory tests at Teledyne Webb indicated that even the OSU 200 m pump endurance record could be significantly extended by flying to 90% of its design depth rather than the full depth of 200 m. We also knew that flying deeper would mean less time in the most biologically active surface layers, and it would reduce our energy use with fewer cycles on the pump. To better monitor energy use, a newly designed Coulomb meter was developed to monitor how much energy is drawn from the batteries. Based on our theoretical calculation of how much energy was on board, we could use the Coulomb meter as a fuel gauge to tell us how much energy we used, and theoretically, how much we had left. Because the RU17 leak scenario that was most difficult to rule out was a breach in the hull caused by external damage to the CTD, Teledyne Webb Research designed a new pin supports front and back to reinforce the external portion of the CTD sensor. It no longer could be bent by a large animal or used as a pry bar. Internally we would rearrange the weight and balance so that even more of the lighter lithium primary batteries could be set inside. Externally we worked on protection from the biology. Hull sections and the tail cone would be coated with the light rubberized ClearSignal to minimize the need for heavy ablative antifouling paints.

RU27 was constructed at Teledyne Webb Research as an extended payload bay long-duration glider with the above design changes from the start. Like RU17, it was constructed with no altimeter and the payload bay computer removed, requiring the CTD to be hooked directly into the flight control computer. RU27, outfitted with Alkaline batteries, was tested on the Tuckerton Endurance line from February 18 through March 13, 2009 (Figure 1a), making the dangerous trip across the shelf break fishing areas into deep water to test the 200 m pump. While offshore, the steering was tuned to use minimum power yet still maintain a straight course. We collected data on the power usage of all systems and worked to reduce our communications towards our eventual goal of 1.5 Watts daily average power draw for the full vehicle.

With the flight test complete, RU27 was prepared for the second Trans-Atlantic attempt. It was stripped down, fully inspected from the test flight, and completely rebuilt, making as much space as possible for additional lithium batteries. The 435 Lithium C-Cells on RU17 grew to 468 on RU27, an 8% increase. The wings were permanently attached to the wing rails. All exposed surfaces not coated with ClearSignal were painted with anti-fouling paint. Care was taken not to get any paint in the seams between glider sections to cause no interference with the critical O-ring seals. RU27 was christened *The Scarlet Knight* by NOAA IOOS on March 23, 2009. Placed inside the hull was a NOAA coin, a Rutgers 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, and 20 years after the publication of *The Slocum Mission (Stommel, 1989)*.

The flight track of RU27 across the Atlantic is shown in Figure 6, 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. It was now 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 RU15 & RU17, 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 its entire length in less than a month, with only a short delay with 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 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 by an incorrect treatment of the combined drifter and satellite altimetry by the data assimilation component of the forecast system. Assimilation of the drifter data acted to spin up an anti-cyclonic eddy, but altimetry data is only flagged for assimilation when there is a change in altimetric sea surface height over time. In this case, the altimetry data said there was no anticyclonic eddy in the region, and that this result was constant for weeks. As a result, no altimetry was passed through the assimilation scheme to remove the Phantom Eddy from the forecast. 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 unpainted seams between the five glider 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 where photographically documented and then removed by hand by divers while RU27 remained in the water. Once cleaned and flight characteristics 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. From that point, 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 1000 satellite phone calls to report data and receive new commands. Total power used was 7750 Watt Hours, equivalent to a 100 Watt light bulb turned on for 77.5 hours, or just under 3.25 days.

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 Summer Research Institute sponsored by the DHS Center of Excellence for Port Security between semesters. Typically 10 teams of 2-3 students were working in parallel on different aspects of the mission, from watching the weather for winds and waves, validating the ocean current models, monitoring the glider flight performance and its ability to communicate, analysis of the glider data, definition of a safe landing zone, and logistics for recovery. Over 25 multi-authored student research posters where constructed and presented at research meetings from the flight, including one summary student poster representing the entire team that was presented at Ocean Sciences. The Dean of Undergraduate Education sponsored events for the students to tell their story and inspire other undergraduates to get involved. Our class size doubled each semester, from 3, to 7, to 13, to 26 over the two years covering the flights of RU17 & RU27.

In addition to oceanography classes, the Trans-Atlantic flight was used as the subject of a documentary filmed, edited and produced by an 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* is now a finalist in the 2010 Blue Ocean Film Festival in Monterey. 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 that has also been demonstrated on the floor of the Smithsonian in DC.

Inspired by discussions with their student collaborators in Spain and Portugal, and early in the flight, 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 with the news, made landfall. On December 9, 2009, still aboard the recovery vessel *R/V Investigador,* RU27 made landfall in Baiona.It was here in Baiona that the Spain’s Minister of Development officially returned RU27 to the U.S. delegation, lead by representatives of the U.S. 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*.

**Results from the RU27 Crossing.**

A partial data set collected by RU27 is shown in Figure 7. Temperature (Figure 7A ) and the northward depth averaged velocity (Figure 7B) were combined to provide a proxy for heat transport (Figure 7C). The same variables generated from an ocean numerical model (HyCOM) are plotted in Figures (7D,E,F). Starting on the Mid-Atlantic Bight shelf in late April and continuing into early May as RU27 crosses the Slope Sea, temperature in the glider data and the model is cold, around 11C. Currents are generally slow to the south for both glider and model. From May 7 through June 5, RU27 navigates the warm water of the Gulf Stream. The glider data indicate, as expected, that the warm water of the Gulf Stream is above 18 C in the 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 W to 55W, and both turn to positive north-south 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 18C is found 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 navigates 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/sec north-south currents, depending on the side of the eddy. Therefore calculating the correct heat transport becomes a challenge of 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/sec in the north or south direction. The surface layer of the ocean is observed to cool as winter approaches. Water less than 14C rises above the 100 m depth. By December, the water column is nearly uniformly cool near 14 C. Heat transport is small compared to the western side of the basin earlier in the year.

**Results from the Thermal Glider Cook**

Since the completion of the RU27 journey, the trans-Atlantic efforts continue. The goal is continue to develop a sustained capability to explore the ocean basins, their mesoscale variability, and their interactions with the atmosphere, with a long term goal of improving our spatial estimates of ocean heat flux between the tropical and temperate oceans. To this end, the Rutgers undergraduate education program is continuing the collaboration with Teledyne Webb Research and their efforts to further the development of Thermal Gliders. Unlike the Slocum Electric gliders that use a battery powered pump to change their buoyancy, Slocum Thermal Gliders use a buoyancy engine that harvests energy from the thermal structure of the ocean. In 2010, Rutgers undergraduate education programs turned their attention towards the ONR-sponsored Thermal Glider named James Cook and its attempt to cross the Atlantic through the middle of the North Atlantic Gyre. This line would spatially coincide with international RAPID Climate Change program focused on understanding the meriodional heat flux across this part of the basin. The RAPID program is designed to monitor the North Atlantic Meridional Overturning Circulation, focused on a Trans-Atlantic section along 26.5 N, the location of the maximum north-south heat transport.

Here we present similar sections as plotted for RU27 in Figure 8 for temperature (8A,D), meridional velocity (8B,E) and the product (8C,F) for the glider Cook (left column) and the HyCOM model (right column). In this case, the warm, greater than 18 C water extends to depths of 300 m to 500 m, demonstrating the advantages of a deep glider in resolving the temperature structure across the center of the basin-wide gyre. The thermal structures between the data and the model are quite similar. There is more variability in the depth of any isotherm on the western side of the transect. On the eastern half, the isotherms exhibit a broad arch, rising up through the first half of June 2010 and moving back down through the second half of June 2010. The current structures seen in the model and the glider, however, are quite different. The glider, by necessity, only returns the depth average of the current over the depth of the undulations, in this case 1200 m. The current structure in the model forecast is far from constant with depth. Significant vertical shear is observed near the base of the seasonal and permanent thermoclines. Near the surface, current speeds in the model reaches + 50 cm/sec. Currents near the bottom are much smaller, rarely exceeding 10 cm/sec. As a result, most of the variability in the currents is observed above 800 m. Below this depth the heat transport is low and there is little variability across the section. Assuming the depth average current applies to the full profile produces a very different picture of the heat transport for the glider as the vertical structure is smeared, with too little transport in the warmer surface waters and too much in the cooler bottom water.

The above observations are illustrated during a case study chosen on May 20, 2010, which is central to the most prominent southward heat transport event in the data and the model. This transport is driven by a strong southward flowing jet on the eastern side of an anticyclonic eddy. The jet is observed in both the satellite altimetry product (Figure 9B) and the HyCOM model (Figure 9H), but with slightly different orientations. In this case, Cook flew across the northern side of an anticyclonic eddy, experiencing strong currents to the north on the western side of the center and strong currents to the south on the eastern side. The current and temperature structure reflect this, with strong northward currents switching to strong southward currents. The net effect on heat transport is thus small. As the glider Cook flies east out of this eddy, it proceeds to fly between two anticyclones, one to the north and one to the south. The model and glider are in good agreement with the northern eddy, but less so for the southern eddy. Instead of a distinct large eddy on the south, the model has evolved a string of small eddies with multiple centers. There is a resulting difference in the direction of the current in the jet near 62.5 W. In the altimeter and glider data, the jet is oriented nearly north-south. In the model, the jet is at an angle, flowing from northwest to southeast. This causes a large difference in the east-west transport, since the glider suggests little heat transport. Meridional heat transport for the glider and the model will be similar in magnitude and direction.

Profiles of temperature, velocity and a proxy for heat flux are plotted from the HyCOM model (Figure 9D,E,F) for May 20 near the center of the southward flowing feature in Figure 9G. To aid in interpolation, we define a temperature anomaly by subtracting the 1200 m temperature from the profile. The transport proxy is calculated as the product of the meridional velocity and the temperature anomaly profiles. Two comparisons are made.

The first comparison (Figure 9H) samples the HyCOM model similar to a glider. For a given profile depth between 100 m and 1200 m in increments of 100 m, the depth average currents from HyCOM are calculated as if they had been sampled by a virtual glider. The virtual glider and model fluxes are compared by taking the ratio of the calculated heat transports for each profile. The shallower the dive, the more likely the two are going to agree.

The second comparison statistic (Figure 9I) calculates the resulting heat transport in the HyCOM model if the depth of the profile is reduced in increments of 100 m. For comparison purposes, the ratio of the temperature anomaly transport at the new depth is divided by the temperature anomaly transport from 0 to 1200 m. As the depth of the comparison profile increases, the ratio approaches 1. For depths in the range of 600 m to 800 m, the temperature anomaly value is within 90% of the full depth value. This indicates that not all of the profile is needed to get good estimates of the heat transport.

Figures 9H,I show that two competing interests are at work when using gliders to calculate heat transports. The deeper the profile, the more the actual temperature profile is sampled. The shallower the profile, the better the depth average current represents the velocity profile. Since heat transport is the product of the two, design of glider missions to support the assimilation of both temperature and velocity profiles should consider their operating depth carefully to meet the design needs. Going deeper does not necessarily provide the best data to improve the model for heat transport calculations.

**Evolving the Undergraduate Oceanography Experience.**

Traditional marine science programs are often structured around a classical model of classroom learning in the first 2-3 years at the University after which a small minority of the students gain field experience by working in research labs and partaking on research cruises. This has been effective model for developing future Ph.D. students over the last 50 years. Unfortunately given the challenges facing society today there is a greater need then grooming future PhD students. It is critical that the undergraduate experience expands ocean literacy across all of the sciences and humanities. This is especially important as 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 pursue 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. The new approach has three 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 allow 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, which joined the Atlantic crossing effort of RU17 were freshmen and sophomores. The RU17 attempt, failure, engineering analysis, construction of RU27 and eventual successful Atlantic crossing was a three year process; therefore for the students to experience the full adventure need to be engaged early in the University career to realize the fruits of their labor. Therefore designing strategies to capture the students as they enter the University is critical.

This lead us to develop Oceanography House which is a dedicated freshmen 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 will meet weekly with professors and upper-class students to focus ongoing scientific efforts. Computers at Oceanography House are optimized to provide the students 24-hour access to the full resources of the RU COOL operations center in the Marine Sciences Building. The formation of this living learning community grows out of the experience of the trans-Atlantic glider efforts.

*Developing a near peer community is important to 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 in freshmen have a wide range of expertise, represent a wide range of disciplinary interests spanning from oceanography to English, and mirrors the ethnic and cultural diversity of the Rutgers student body, one of the most diverse state research universities in the United States. 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, which provides them experience in the teaching. Many of the students who decide to not pursue graduate school, often become teachers. This is particularly important there is a critical need to improve science education at the primary education level. To assist in this process, the students are provided the opportunity to take a class called “Communicating Ocean Sciences” which is dedicated to developing the skills required to be a good public science teacher by providing the a firm found in communication techniques and pedagogy. Here the goal is to provide a broad ocean literacy beyond oceanography and Earth System science majors.

*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 (see above), student projects 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, researched the history of the Spanish port cities to help a develop Scarlett knight narrative. These individual components were then combined to assist the recovery of the glider after 221 days at sea.

**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, entraining students along the way. 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 was the first dedicated scientific circumnavigation of the globe (Figure 10). It took 3.5 years, leaving England in December, 1872 and returning in May, 1876, and it traversed 111,000 kilometers, 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. The present thermal gliders are designed so that the material in the heat engine freezes and melts at 10 C. About 1.5 hours is required below this isotherm for the material to completely freeze, a mission critical requirement. But the freezing point is adjustable. Thermal gliders work best when there is a large temperature difference between the surface and the bottom of the undulation, typically about 15C. Winter and Summer forecasts from the HyCOM model (Figure 10) indicate that thermal gliders can be tuned to cover much of the subtropical ocean basins and the tropics. Our own tests with Cook 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 in our classrooms. Our students have 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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**Tables**

Table 1. Battery pack comparison for a standard Alkaline-powered coastal glider and a Lithium-powered trans-Atlantic glider.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 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 Watts | 34 Days | $5.22 | $1,200 |
| RU27 | 435 | 88.5 kJ | 1.5 Watts | 352 Days | $50.60 | $22,000 |
| Factor | 1.9 | 4.1 | 1.33 | 10.4 | 9.7 | 18.3 |

**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 & fishing activity. |
| 17 | Dec 11 | Landfall in Baiona, Spain |