The Challenger Glider Mission: A Global Ocean Predictive Skill Experiment

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Abstract*— Ocean forecasting models are an extremely valuable tool for understanding Earth's oceans. Current ocean forecast models assimilate satellite sea surface height and temperature data as well as temperature/salinity profiles from the Argo network of over 3,000 drifters. Though assimilating datasets from these drifters is pertinent, it does provide some limitations. Observing System Simulation Experiments routinely indicate that additional profile data, especially profile data that crosses frontal features, are the most influential at reducing forecast uncertainty. Since Argos drifters cannot be controlled and are subject to the oceans currents, areas that would provide critical data to ocean forecasting models are often under sampled. A potential solution to this problem would be to implement datasets provided by Slocum Gliders into the ocean forecasting models. These Autonomous Underwater Gliders are not as limited by the conditions of the oceans as Argos drifters are. Through their ability to sample virtually anywhere in the ocean, they will be able to bridge the gap left by using Argos drifters. This project aims to show the validity of including glider data into forecasting projects by comparing temperature, salinity and surface current projections made by two different ocean models (RTOFS and MyOcean) to the in-situ datasets collected by two gliders: one in the North Atlantic (Silbo) and one in the South Atlantic (RU29). There was a larger variance found between the two models for temperature and salinity compared to Silbo at the 200 m level than the 800 m level. At 200 m there was also an interesting case of disagreement between the MyOcean model versus the RTOFS model and Silbo's observations. There was a considerable peak in values of salinity and temperature with the MyOcean that was not present with the other two sources of data. The results show that there is good reason for ocean forecasting models to incorporate glider data. As for the temperature comparison with RU29 at 200 m, the RTOFS model was typically 2°C too cold, while the MyOcean model was fairly accurate. For 800 m the RTOFS model was about 1°C too cold, while the MyOcean model was about 1°C too warm. The salinity projections made by both models at both depths were always consistently accurate with RU29. These results indicate that the models, while useful, are not free of error and can be improved by incorporating datasets from gliders. Improved ocean forecasting models will have many applications, most importantly the increased ability of predicting the paths of intense storms, especially hurricanes, which are heavily influenced by ocean conditions.

Keywords — Ocean Forecasting; Autonomous Underwater Gliders; Challenger Glider Mission.

I. INTRODUCTION

Autonomous Underwater Gliders have a long and successful history of regional deployments serving scientific, societal, and security need. Application areas range from pole to pole and include the range of water depths from shallow coastal seas to the deep ocean. Glider deployments covering the basin scale are much fewer, with some well-known exceptions including the Woods Hole to Bermuda line that crosses the Gulf Stream and the Atlantic Crossing line that follows the Gulf Stream (Figure 1). New technologies for extending glider endurance are making year-long deployments and regular basin-scale missions a new reality (Figure 2). The new technologies include the capacity for more on-board lithium battery power, lower power sensors and energy harvesting to extend duration, and biofouling protection to maintain flight control and sensor calibrations.

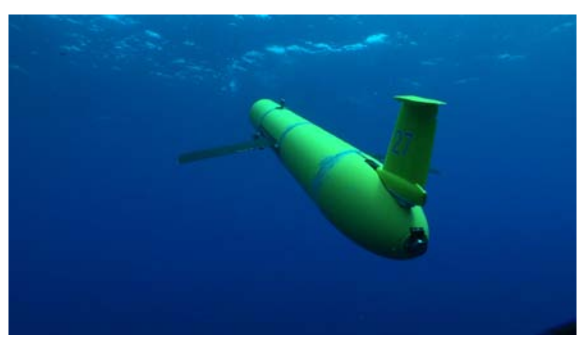

Figure 1: A photograph of RU27, an autonomous underwater glider that successfully crossed the Atlantic Ocean in 2009.

We have recently begun a globally coordinated underwater glider mission dedicated to research and education to demonstrate this new technological capability. The Challenger Glider Mission will include operation of a fleet of gliders on simultaneous basin-scale missions that revisit the historic track of the H.M.S. Challenger's first dedicated scientific circumnavigation. The scientific questions to be investigated focus on an assessment of the quality of the ensemble of available global-scale ocean models. The mission has already begun with one global-class G2 Slocum Electric glider deployed in the North Atlantic (Silbo) and a second deployed in the South Atlantic (RU29). These two gliders have already completed over 803 days at sea covering more than 15,000 km.

The goal is to match the 128,000 km distance covered by the H.M.S Challenger by 2016, the 140th anniversary of the research vessel's return to Great Britain. This goal can be achieved in 1 year with 16 gliders simultaneously flying 8,000 km legs following the gyre circulation around each of the 5 major ocean basins (Figure 3). Two additional Slocum Thermal gliders are scheduled to be deployed in the Pacific in 2013.

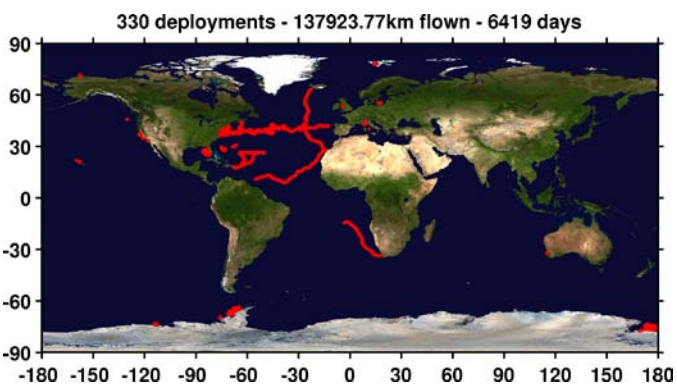

Figure 2: A map of the history of tracks covered by Rutgers Coastal Ocean Observation Lab's gliders. Basin scale missions, in collaboration with Teledyne Webb Research, Universidad de Las Palmas de Gran Canaria.

The immediate scientific goals are to assess the current capabilities of the existing international suite of global ocean forecast models. The existing global ocean forecast models assimilate satellite sea surface height and temperature data as well as temperature/salinity profiles from the Argo network of over 3,000 drifters. Still, observing System Simulation Experiments routinely indicate that additional profile data, especially profile data that cross frontal features, are the most influential at reducing forecast uncertainty. Since the location of Argo drifters cannot be controlled after they are deployed, some regions are critically under sampled, and strong boundary currents are often unresolved.

Figure 3: The projected paths of the Challenger Glider Mission.

This study will report the results of student investigations that compare the glider temperature and salinity profiles, along with depth-averaged currents, with the forecasts from the international ensemble of global ocean models. Preliminary student results indicate that the general structure of the model-generated temperature and salinity profiles agree well with the glider, but differ in the details. Much larger differences are found between the model and observed currents. Along the glider-tracks collected to date, the U.S. global model is found to compare more closely to the observations in the North Atlantic, while the European model is found to compare more closely in the South Atlantic.

As an effort to improve the forecasting capabilities of ocean models, in-situ measurements of salinity, temperature, and currents, collected by gliders, were compared to conditions predicted by the models.

II. Methods

The first ocean forecasting model used in this comparison was the MyOcean model. This model is a product of Mercator and is a collaborative effort between European countries including the United Kingdom, France, Germany and Denmark. This model provides projected data for velocity, temperature, and salinity components of the water column in 5 m bins of depth, for the first 30m, and then in 10m bins for the next 70 m. The second ocean forecasting model used for comparison was the RTOFS (Real Time Ocean Forecast System) model. This model is a product of the National Center for Environmental Prediction (NCEP).

The primary oceanographic sensor on the G2 gliders is a SeaBird pumped Conductivity, Temperature and Depth (CTD) sensor. Temperature and salinity profiles are processed as described in Kerfoot et al. (2010), a process that includes correction for the thermal inertia of the conductivity sensor. RTOFS and MyOcean forecasts are harvested and archived each day in a 1000 km x 1000 km box surrounding the glider location. Glider data and model forecasts are compared every day to help determine new waypoints along paths with favorable currents, including new 3-D visualization tools developed at the Universidad de Las Palmas de Gran Canaria.

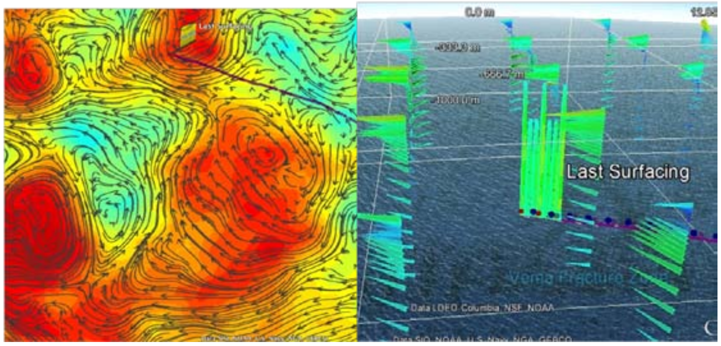

Figure 4: Example of the path planning tools that can be created using data from the ocean forecasting models RTOFS (left) and MyOcean (right).

The comparisons made between the glider data and the projected data formulated by the models were produced by analyzing estimates of temperature, salinity, and surface currents made by each. The data from the models was pulled the internet databases, while the glider data was collected by Silbo (Figure 5a) and RU29 (Figure 6a). The in-situ glider data was considered to be the ground truth conditions of the water column. The analysis was done by calculating the difference between conditions that the glider reported and the conditions that the models forecasted, as well as the differences between the two models. A series of MATLAB scripts allowed the data to be processed and various profiles to be made.

The plots for both Silbo and RU29 compare the 200 m and 800 m values of temperature and salinity as sampled from the gliders to the outputs from the RTOFS and MyOcean models. The 200 m level was chosen as a representation for the near surface layer of the ocean while the 800 m level was chosen to compare the deeper range of the gliders' approximately 1000 m maximum depth. There is a set of plots for each glider for each variable and depth level. To compare surface currents, the conditions reported by the glider were plotted against the conditions projected by the models, using Google Earth.

Figure 5a: The portion of Silbo's track that was used for comparison to the models, beginning at the green dot and ending at the red dot. This track represents an east to west section across the southern side of the North Atlantic Gyre.

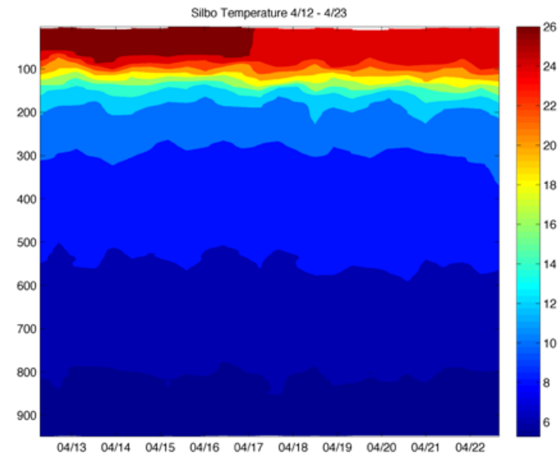

Figure 5b: The temperature dataset from Silbo, used for the case study of 4/12/13-4/23/13.

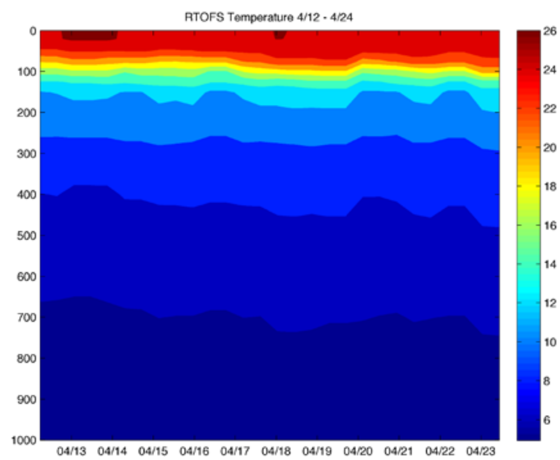

Figure 5c: The temperature dataset from the RTOFS model, used for the case study of 4/12/13-4/23/13.

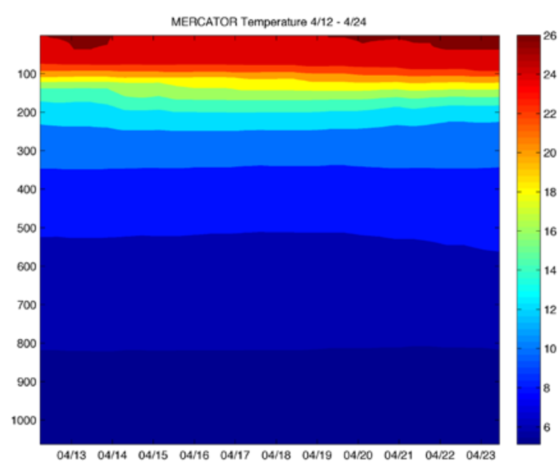

Figure 5d: The temperature dataset from the MyOcean model used for the Silbo case study of 4/12/13-4/23/13.

Figure 6a: The portion of RU29's track that was used for comparison to the models, beginning at the green dot and ending at the red dot. This track represents a south to north section along the eastern side of the South Atlantic Gyre.

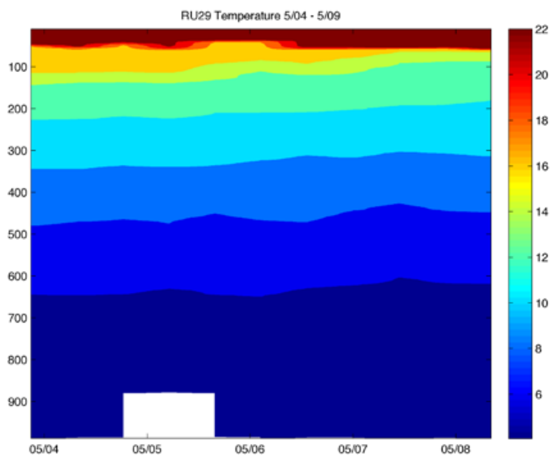

Figure 6b: The temperature dataset from RU29, used for the case study of 5/6/13.

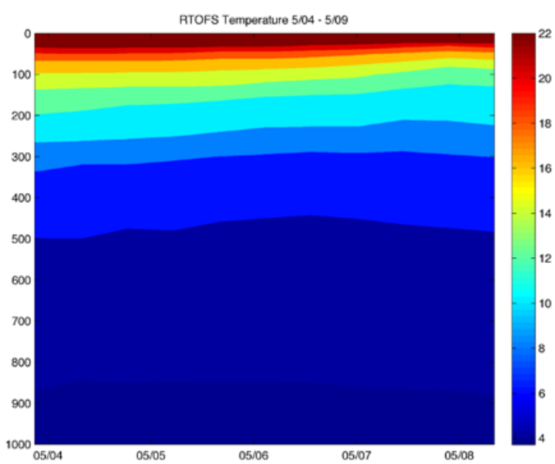

Figure 6c: The temperature dataset from RTOFS, used for the case study of 5/6/13.

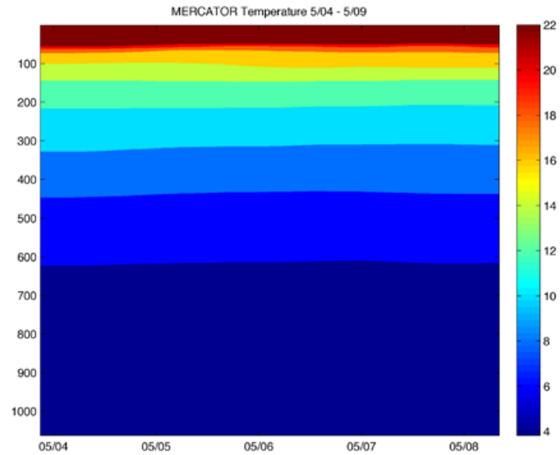

Figure 6d: Temperature dataset from the MyOcean model used for the RU29 case study on 5/06/13.

III. Results

A. Silbo

There is a 37 day period starting on April 9th, 2013 and ending on May 15th, 2013 that is plotted to compare the recorded values from Silbo to the two models on a daily basis (Figure 7). Beyond May 15th is when Silbo experienced its problems and was forced to abort so Silbo was no longer gliding and recording ocean profiles.

For the comparisons of salinity, at both 200 and 800 m the RTOFS model is more consistent with the data collected. At 200 m the salinity of the MyOcean model is seen to have a broad peak in which it diverges greatly from the observed temperatures from Silbo. By around the 24th of April the MyOcean model is shown to have recovered and then generally remains close in accuracy. The RTOFS model however is more accurate overall, especially with respect to the trends over the time period sampled. The fluctuations over time that Silbo recorded are also relatively well portrayed in the RTOFS salinity values at this level. The MyOcean model is off by about 0.6 PSU versus the Silbo observations and the RTOFS model during the MyOcean peak.

The consistency, accuracy and trends of the temperature plot for Silbo at 200 m are very similar to the 200 m plot for salinity. There is a jump or increase present in the MyOcean model approximately between the dates of April 10th and April 24nd where at the same time the RTOFS model shows one of its most accurate periods. The temperature between the MyOcean model and Silbo differ as much as 2-3°*C* between those dates. It is also evident from this plot that the RTOFS model is consistently cooler than the MyOcean model.

At 800 m the salinity differences of the models to the measurements from Silbo were considerably less than those found at 200 m. Both ocean models were found to be close in comparison to each other and any differences from either model rarely exceeded 0.1 PSU. The RTOFS is the better performer for the first half of the month time series but only by a small factor.

The temperatures at the 800 m level tell a different story than the 200 m level. Here the MyOcean model shows greater accuracy over the RTOFS model. Similarly to how the 800 and 200 m levels of salinity compared, the difference between the 800 m glider temperatures and the models did not have as great of a range as did the 200 m level. It is noticeable that the RTOFS model is about 0.5°*C* too cold at this 800 m level.

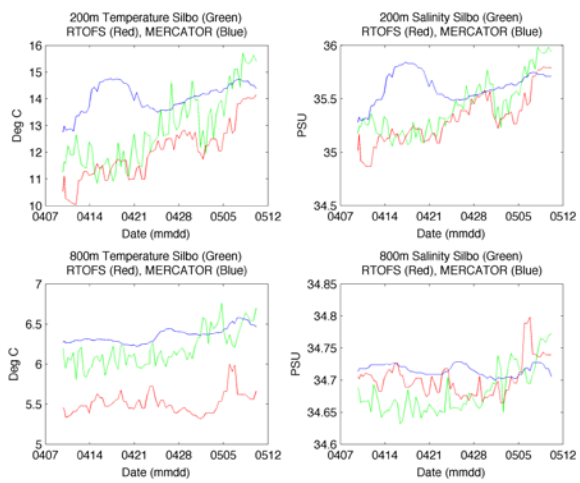

Figure 7: Comparisons of Silbo (green) with RTOFS (red) and MyOcean (blue) model data of temperature at 200m (top left), 800m (bottom left) and salinity at 200m (top right) and 800m (bottom right).

B. Silbo Case Study

Within Silbo's time series plots there is one feature that is most prevalent at the 200 m level which has been explored further here. As discussed earlier there is a period between 4/13/13 and 4/22/13 where there is a jump in the 200 m salinity and temperature as modeled by MyOcean. The RTOFS model however does not contain this feature and remains more accurate to the observations that Silbo recorded.

Figures 8a and 8b show two maps that display Silbo's path across a section of the Atlantic Ocean. There is a point labeled that represents the glider's surfacing location during the day of April 18th. This date was chosen because it falls near the MyOcean peak of temperature and salinity. The maps show the ocean temperatures and the ocean currents at 200 m with the upper being the RTOFS model run and the lower being the MyOcean model. Comparing the two vector fields alone on this same day show that there is a large amount of disagreement between the two and many of the eddy features are opposite in flow direction.

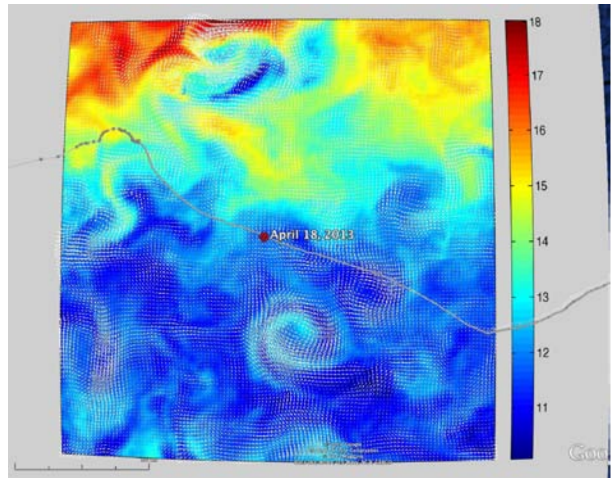

Figure 8a: RTOFS 200m temperature and currents on April 18th, 2013. The glider position is marked by the red dot.

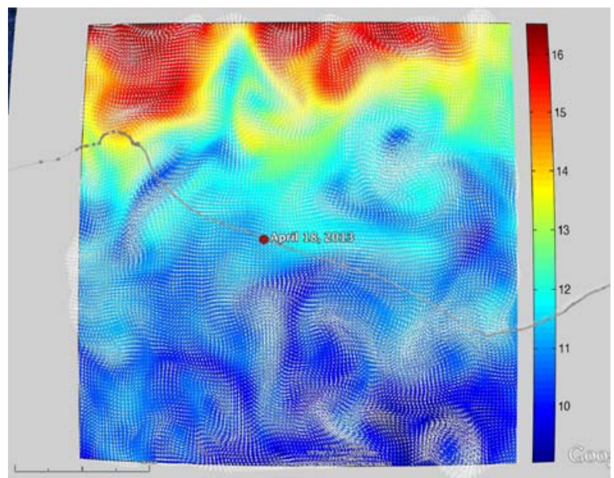

Figure 8b: MyOcean 200m temperature and currents on April 18th, 2013. The gliders position is marked by a red dot.

The RTOFS model displays currents at 200 m that are coming from the southeast at Silbo's location which would be providing cooler temperatures (Figure 8a). The MyOcean model however has currents at this level coming from the northeast towards Silbo and with them bringing comparatively warmer temperatures. The warmer area of water that MyOcean shows being pulled south is what it expected Silbo to fly through and would explain the broad peaked increase in temperatures (Figure 8b). At the surface, warmer water temperatures in the Northern Hemisphere would be to the south and closer to the equator. At 200 m, however, the warmer waters on the maps are shown to the north. This is the result of North Atlantic Gyre that creates a deeper layer of warm water which is visible at depth and is independent of what some of the surface solar-heated waters may be. In

Figure 9 two profiles, one for temperature and one for salinity show the entire depth range down to 1000 m. The warmer temperatures of the MyOcean model are visible here extending beyond the 200 m level (Figure 9).

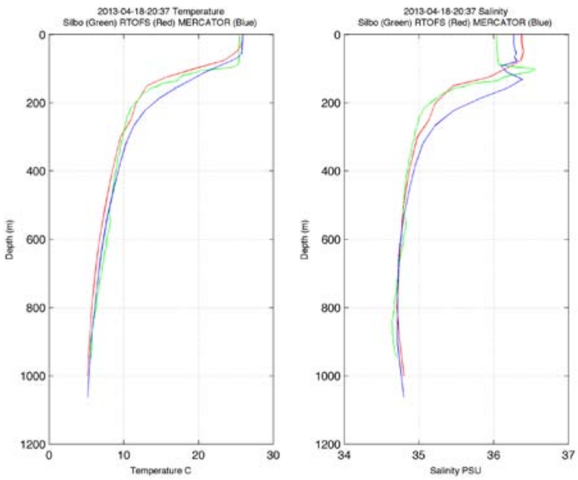

Figure 9: (Left) Profile of temperature comparison between Silbo (green), RTOFS (red) and MyOcean (blue) for 4/18/2013. (Right) Profile of salinity comparison between Silbo (green), RTOFS (red) and MyOcean(blue).

C. RU29

A time period consisting of 82 days, starting February 22nd, and ending May 15th was used for comparison with the two models (Figure 6a). These data sets were compared separately at 200m and 800m depths with respect to temperature and salinity. During this time period RU29 had begun to leave the coastal waters of South Africa and journey northeast towards the equator.

At 200m of depth, the RTOFS model was always about $2°C$ too cold, while the MyOcean model was quite accurate (Figure 10). As this time series progresses, the temperature reported by all three data sets show that the ocean is getting progressively colder. This corresponds to the transition of Summer to Winter in the Southern Hemisphere. Both models show an interesting spike in temperature around 3/25/13, but they are in different directions. The RTOFS model drops by about $1°C$ during this time, while the MyOcean increases by about $1.5°C$. The glider does show a slight decrease in temperature during this time, but not on the magnitude that the RTOFS model predicts.

At 800m depth, the RTOFS model was typically about $1°C$ too cold, while the MyOcean model was typically about $1°C$ too warm. As this time series progresses the three different datasets show a similar trend of a slight increase in temperature. This slight increase corresponds to the gliders approach to the equator. Neither model is ever off by more than $1°C$ during this time series.

At 200m depth, both models were very accurate in projecting salinity. The RTOFS model typically predicted low by about 0.2 PSU while the MyOcean model was pretty much spot on. Both models were also fairly accurate at projecting salinity at 800m depth. The RTOFS model typically over predicted but by only a very small margin. MyOcean again was pretty much spot on.

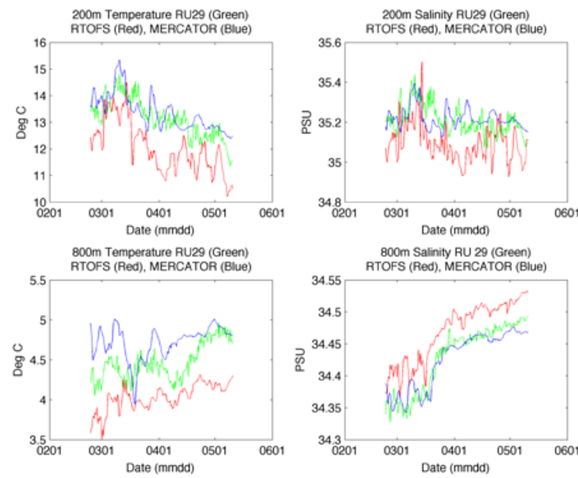

Figure 10: Comparisons of RU29 (green) with RTOFS (red) and MyOcean (blue) model data of temperature at 200m (top left), 800m (bottom left) and salinity at 200m (top right) and 800m (bottom right).

D. RU29 Case Study

Another day that provided results worth analyzing further was May 5th, 2013. On this day the MyOcean model depicted two different eddies, one north of RU29's location, and one south (Figure 11a). The eddy north of the glider was flowing in a counter-clockwise direction, and the eddy south of the glider was flowing in a clockwise direction. Since RU29 was located in the Southern Hemisphere, the southern eddy would be considered a warm eddy and the northern one a cold eddy. In order to verify that this phenomenon was actually occurring in the ocean, these projections were compared to both the RTOFS model and the glider data (Figure 11b).

RU29's location during this study is marked by yellow pins, and the currents it reported by red lines. The RTOFS model projections showed no sign of either eddy. The surface currents reported by the glider appear to be almost opposite of what the MyOcean model was predicting, and seem to agree more with the projections of the RTOFS model.

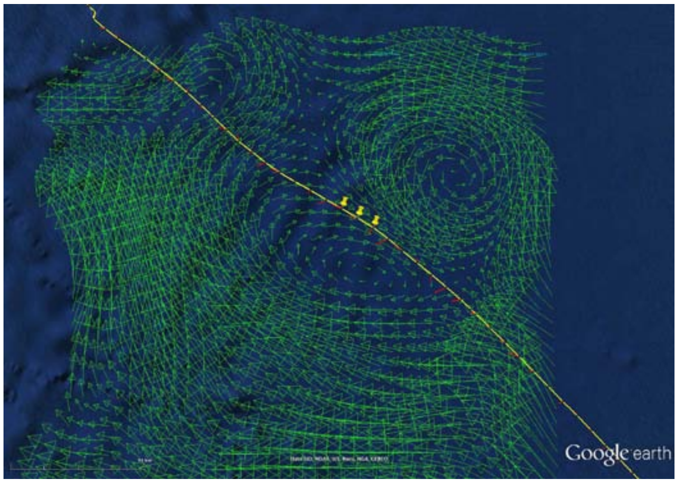

Figure 11a: MyOcean surface current projections and surface currents reported by RU29 for 5/06/2013.

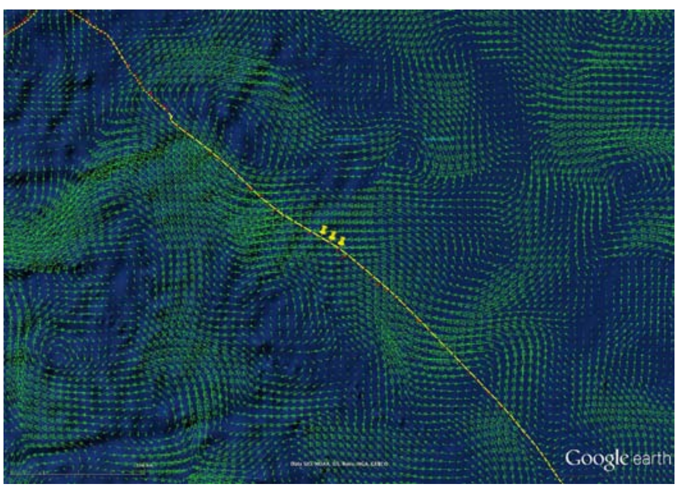

Figure 11b: RTOFS surface current projections and surface currents reported by RU29 for 5/06/2013.

In order to get a better understanding on whether the eddies were a valid feature or not, the salinity and temperature profiles of the models and RU29 were analyzed (Figure 12). According to these profiles, the data collected by RU29 agrees more with the MyOcean model for both temperature and salinity. So even though the surface currents experienced by RU29 were directly opposite of what the MyOcean model predicted, the MyOcean temperature and salinity projections were quite accurate.

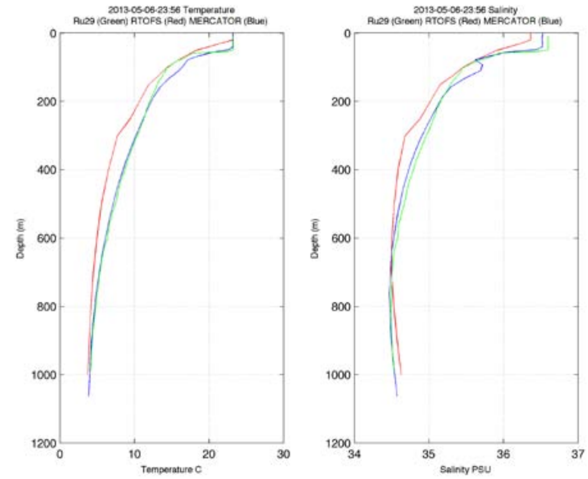

Figure 12: (Left) Profile of temperature comparison between RU29 (green), RTOFS (red) and MyOcean (blue) for 5/06/2013. (Right) Profile of salinity comparison between Silbo (green), RTOFS (red) and MyOcean(blue).

IV. Discussion

The value of ocean forecast models has advanced well beyond scientific curiosity-driven research. The world's major forecast centers currently run operational global forecast models that are eddy-resolving, data assimilative, and are distributed free-of-charge to a wide variety of users. Global-scale ocean assimilation data include satellite-derived sea surface temperature and sea surface height, as well as the global array of Argo profiling floats and surface drifters. Forecast skill continues to improve, yet many offshore operators are faced with the same set of questions: (1) How good are the global ocean forecast models? (2) Can ocean forecasts for a specific area be improved through the use of nested regional-scale models? (3) Or can better improvements be obtained by locally enhancing the observations in either the global-scale or nested models?

Autonomous underwater gliders provide a means to test ocean models. Unlike drifters & floats, gliders also travel under their own power. They can be programmed to fly into areas with expected high forecast error and provide valuable assimilation data across fronts along the way. The model validation data includes not only the glider's subsurface temperature and salinity profiles, but also their depth averaged and surface drift velocity estimates. Depth averaged velocity profiles are a significant augmentation of the already invaluable Argo profile data. Model-derived temperature and salinity profiles often compare well to observed Argo and glider profiles, but as we see in the two case studies developed here, the model currents can be in opposite directions and the glider depth averaged velocity is required to discriminate.

At the surface, the two global ocean models compared here have very similar characteristics. This is not unexpected, since both are assimilating similar sea surface temperature and sea surface height products. Subsurface, the models look very different, especially at 200 m, near the seasonal thermocline. RTOFS contains many distinct and highly circular eddies at this level, while MyOcean exhibits many interconnected and meandering filaments wrapped around the same highs and lows. At times, the MyOcean filamental flow directions line up with the RTOFS eddy circulation, and at other times, they are in direct opposition. In the first case study presented here, the long filaments resulted in the advection of anomalous warm water from the southern edge of the North Atlantic gyre into the colder subsurface water to the south. The filament persisted for the full 10 days it took the glider to cross it, with no sign of the anomalously warm water in the glider data. In the second case study, surface currents from both models agreed well with the surface drift of the glider every time it surfaced to communicate. At 200 m depth, however, currents in the two models were exactly opposite, one generally in the direction of surface flow and one opposite. The glider depth averaged velocity indicates that one of the models did the better job of forecasting the observed temperature and salinity profiles, but that information was insufficient to decide which model produced the better velocity forecast. Neither model was in agreement with the observed currents at depth.

The two case studies highlight the need for a broader and more systematic validation study that could be conducted with a fleet of gliders with persistent coverage over a long period. In this paper we propose a global model skill assessment study focused on some of the more difficult to reproduce parts of the ocean, the edges of the major gyres. It is in these regions that glider observations may prove their greatest value in global model assimilation and validation by combining velocity profile observations with collocated standard CTD profiles. While surface parameters are important for many applications like Search and Rescue, vessel routing and floatable tracking, the fidelity of subsurface forecasts is required in other applications, in particular, understanding life cycles within pelagic ecosystems, subsurface pollutants, and upper ocean heat content for tropical storm intensity forecasting. Gliders provide the critical dataset to improve models below the surface, an area that is unseen from space, with a dataset that is not currently available from Argo CTD profilers or the global arrays of surface drifters.

V. ACKNOWLEDGEMENTS

The Challenger Glider Mission is growing global partnership of glider operators, scientists, educators and students coordinated by Rutgers University. The results presented in this paper were initiated in a Rutgers research course and completed by two undergraduate summer interns (Collin Dobson & Jeffrey Mart) supported by Teledyne Webb Research. Carlos Barrera teaches the companion course in the Canary Islands. Glider path planning and model/data comparison activities are led by Nilsen Standskov and Antonio Ramos. With cyber infrastructure support provided by John Kerfoot. Glider operators include Chip Haldeman, Dave Aragon, Tina Haskin (Rutgers) and Ben Alsup (TWR). Silbo was donated by Teledyne Webb Research and Challenger (RU29) by Rutgers. The RU29 deployment in South Africa was enabled by the University of Cape Town, The Nansen-Tutu Center, Sea Technologies, and the Department of Environmental Affairs. RU29 mission support is provided by U.S. IOOS. Support for the Pacific Basin Thermal Gliders is provided by ONR with path planning led by students in the U.S. Naval Academy.

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