

Underwater Glider Observations for Atlantic Tropical Cyclone Studies and Forecasts

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ABSTRACT

The use of underwater gliders has become widely used to also include upper ocean observations for tropical cyclone intensification studies and forecasts. This observational platform, which can readily obtain and transmit data in real-time while the ocean is affected by hurricane-force winds, has proven to be efficient for assimilation in numerical models and analysis. Several government laboratories and academic institutions are currently operating gliders in the tropical North Atlantic Ocean and Caribbean Sea, regions where hurricanes form and intensify. This manuscript summarizes key components of these efforts and the main results that have been derived from glider observations. Since there is currently no sustained ocean observing system geared towards hurricane intensification studies and forecasts, gliders are being considered together with other ocean observations to fill this critical gap under a multi-institutional effort.

1. INTRODUCTION

The tropical Atlantic basin is one of seven global regions where tropical cyclones (TC) are commonly observed to originate and intensify from June to November. On average, approximately 12 tropical storms translate through the region every year (Figure 1), frequently affecting coastal, highly populated areas. In an average year, 2 to 3 of them are categorized as intense hurricanes. Given the appropriate atmospheric conditions, TC intensification has been linked to the upper ocean heat content (UOHC, Mainelli et al, 2008), also referred to as Tropical Cyclone Heat Potential, which can be estimated using both *in situ* and satellite observations. Ongoing Atlantic basin observations are presently geared towards investigating large scale and mesoscale processes in a limited number of locations. A sustained observing system in the tropical North Atlantic Ocean and Caribbean Sea dedicated to measuring subsurface thermal fields in support of TC studies and forecasts has yet to be implemented. Autonomous technologies offer new and cost-effective opportunities to accomplish this objective. Underwater gliders, which can cover the upper 1000 meters, carrying a payload of scientific sensors, can be piloted from anywhere via an internet connection, and transmit data in real-time in virtually all weather conditions. We highlight here some observational efforts which utilize underwater gliders to better understand air-sea processes during high wind events, and are particularly geared towards improving hurricane intensity forecasts. Glider data collected by these efforts are transmitted in real-time to the Global Telecommunication System (GTS), and distributed through the institutional web pages and by the IOOS Glider Data Assembly Center.

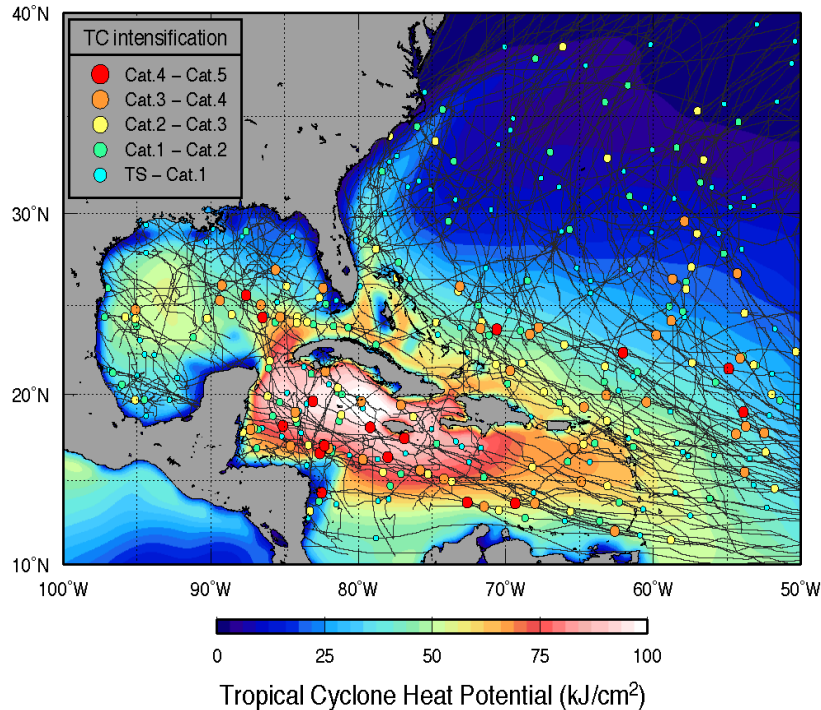


Figure 1. Atlantic hurricane tracks during the period 1993-2010, with color circles indicating the position where they intensified. The background color shows the average TCHP during the same period.

Several independent efforts are currently in place in the Atlantic Ocean using underwater gliders geared towards carrying out studies for hurricane intensity forecast improvements. This article describes these efforts and their principal scientific accomplishments as a prelude to laying the foundations for a coordinated, distributed and sustained observation system targeted specifically toward improving TC research and forecasting capabilities.

An underwater glider network was implemented in the tropical North Atlantic and Caribbean Sea off Puerto Rico by the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) and the Caribbean Coastal Ocean Observing System (CariCOOS), in collaboration with the University of Puerto Rico Mayaguez, the NOAA National Data Buoy Center (NDBC), the NOAA Integrated Ocean Observing System (IOOS), and the University of Miami Cooperative Institute for Marine and Atmospheric Studies (UM/CIMAS) (www.aoml.noaa.gov/phod/goos/gliders). This project is also a component of the NOAA Hurricane Field Program. The sustained and targeted upper-ocean profile observations from these underwater gliders are carried out to assess the upper ocean response to hurricane force winds and to evaluate the impact of assimilating these observations into TC intensity forecasts. Five multiple glider missions have been successfully completed to-date, and approximately 14,000 profiles of temperature, salinity, dissolved oxygen, and chlorophyll have been collected in areas that had previously been poorly sampled. Datasets obtained from these missions include unique temperature and salinity observations sampled under tropical cyclone wind conditions for Tropical Storm Bertha (August 2014), Hurricane Gonzalo (October, 2014), Tropical Storm Erika (August, 2015), and Hurricane Matthew (September, 2016).

The Bermuda Institute of Ocean Sciences (BIOS) launched the Mid Atlantic Glider Initiative and Collaboration (MAGIC) program in 2014 (magic.bios.edu/about) and currently operates a small fleet of three Slocum gliders. They are being used to measure upper ocean heat content and to assess the contribution of small-scale processes to carbon and nutrient cycling in the oligotrophic subtropical gyre. They have also been deployed to record the passages of several TCs, notably Hurricane Fay (2014), Hurricane Gonzalo (2014) and Hurricane Joaquin (2015).

Underwater Slocum gliders have been operated by Rutgers University as a component of a networked coastal ocean observing system in the Mid Atlantic Bight (MAB) since 1999 (Schofield et al., 2015). The ability to profile the full water column in the coastal ocean in hurricanes and Nor'easters fundamentally shifted the technological approach for storm sediment transport studies. These initial studies identified a critical difference between stratified summer and well-mixed fall conditions, where storm-induced mixing of resuspended sediment was inhibited across the intense summer pycnocline, but after the fall transition, sediment was resuspended throughout the full water column with profile shapes consistent with bottom boundary layer theory (Glenn et al., 2008). Full water column optical and acoustic observations of suspended sediment collected by gliders deployed in fall storms Nor-Ida (2009) and Hurricane Sandy (2012) provided a means to validate 3-D numerical models of sediment resuspension and transport where large waves mobilize the sediment bed, and combined wave and current

turbulent mixing suspends the sediment through the full water column where advection by strong currents is significant (Miles et al, 2013; Miles et al, 2015).

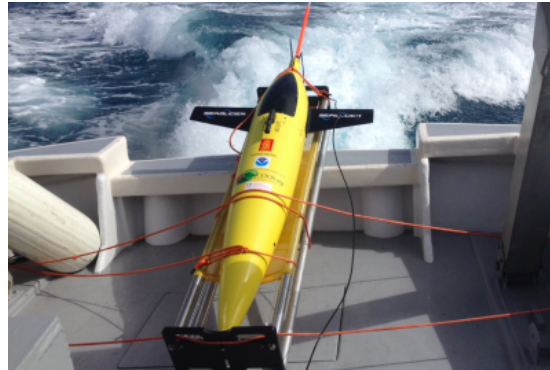


Figure 2. Underwater glider onboard the R/V La Sultana ready to be deployed in the Caribbean Sea prior to the passage of Hurricane Gonzalo (2014).

Underwater gliders have now collected key ocean profile data for air-sea interaction studies beneath hurricanes Barry (2007), Irene (2011), Sandy (2012), Arthur (2014), Hermine (2016), Gonzalo (2014), and Fay (2014). Examples are presented in the two following sections on how underwater glider data were used during several Atlantic hurricane events, with particular emphasis on hurricanes Sandy (2012) and Gonzalo (2014).

2. HURRICANES IRENE (2011) AND SANDY (2012)

One glider deployed beneath Hurricane Irene (2011) revealed stratified summer conditions ahead-of-eye-center surface layer cooling and thermocline deepening as the storm passed over the continental shelf (Glenn et al., 2016). This same work also showed that ocean models indicated that the onshore wind stress balanced by an offshore pressure gradient produced a two-layer baroclinic circulation, and that the resulting shear-induced mixing across the thermocline led to the significant and rapid ahead-of-eye-center cooling. An extensive atmospheric model sensitivity study further indicated that it was the air-sea flux sensitivity to this rapid surface cooling, not track, wind shear, or dry air intrusion, that was the key missing contribution to forecasting Irene's rapid weakening before making landfall (Seroka et al., 2016).

Coastal gliders enabled detailed investigation of the processes responsible for the cooling in two of these storms on opposite ends of the track and seasonal stratification envelope: Barry with an offshore track during early summer, and Irene with an inshore track during late summer. Using the gliders as well as an ocean model, it was found that for both storms the ahead-of-eye-center depth-averaged force balance across the entire continental shelf included an onshore wind stress balanced by an offshore pressure gradient, with shear induced mixing across the thermocline

dominating temperature changes caused by advection (Seroka et al., under review). This indicates that the coastal processes responsible for the ahead-of-eye-center cooling are robust across a wide range of storm types.

Based on the above experiences of gliders sampling the coastal ocean during hurricanes Barry and Irene, a rapid response glider deployment program was developed at Rutgers University, with the specific goal of deploying a glider ahead of a forecasted landfalling TC. A glider-mounted acoustic Doppler current profiler was included as a new sensor with the goal of measuring the currents responsible for advection as well as resolving water column vertical shear to assess the mixing. Fourteen months after Hurricane Irene made landfall, Hurricane Sandy was forecasted to make landfall at nearly the same location on the New Jersey coastline. A storm glider was deployed five days ahead of the forecasted landfall and was piloted offshore. Compare to observations made during the passage of Hurricane Irene in late summer, the mid-autumn storm glider deployment observed a deeper and weaker thermocline at 30 meters depth and a cooler surface mixed layer ahead of Sandy (Miles et al., 2015). As Sandy approached the coast, downwelling favorable winds resulted in offshore advection of the bottom Cold Pool (Houghton et al., 1982), limiting the available supply of cold bottom waters to be mixed into the already cooler surface layer (Miles et al., 2015). Unlike in Barry (early summer) and Irene (late summer), this advection limited the impact of coastal ocean cooling on the intensity of Sandy as the surface cooled by only 1-2°C (Zambon et al. 2014).

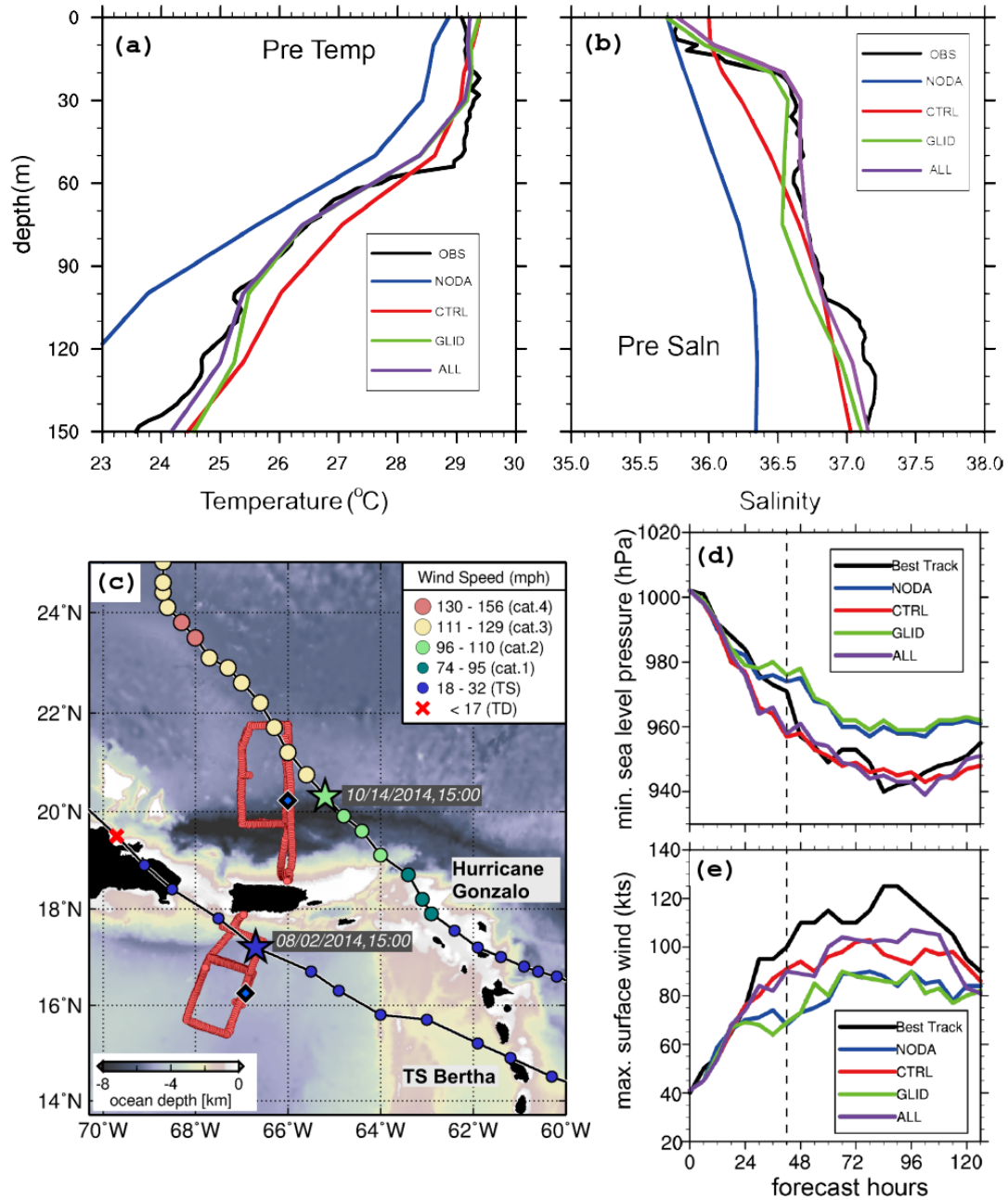
3. HURRICANES GONZALO (2014) AND FAY (2014)

Starting in July 2014, two AOML-CARICOOS underwater gliders were deployed and piloted along predetermined tracks in the Caribbean Sea and in the North Atlantic Ocean off Puerto Rico. During this mission, which took place during July through November 2014, these gliders continuously provided temperature and salinity profile data to 1000m and depth-averaged and surface current velocities. On October 12, 2014, Tropical Cyclone (TC) Gonzalo developed in the tropical North Atlantic. TC Gonzalo travelled ~85 km northeast of the location of the glider as it intensified from a Category-2 Hurricane into a Category-3 storm, with sustained winds stronger than 100kts. This provided a unique opportunity to collect upper-ocean profile observations under hurricane wind conditions. Observations were collected before, during, and after the passage of this hurricane. These observations were also assimilated in the NOAA next generation operational coupled ocean-atmosphere hurricane model at the Environmental Modeling Center to assess the impact of underwater glider observations on hurricane forecasts.

The main finding from the analysis of data from this mission was that when Gonzalo travelled north of Puerto Rico its induced sea-surface temperature cooling was largely suppressed by the presence of a low-salinity layer in the upper 20m of the ocean, normally referred to as a barrier-layer. Maximum upper-ocean cooling reached a value of -0.4°C when Hurricane Gonzalo was the closest to the glider, a value relatively small compared to the upper-ocean cooling reported for other Atlantic hurricanes. The presence of these barrier layers often favors further intensification of TCs. In fact, Gonzalo continued intensifying until it reached the status of a

Category-4 Hurricane (Goni et al., 2015). In addition, the underwater glider data collected during Hurricane Gonzalo was assimilated into the high-resolution Hurricane Weather and Research Forecast (HWRF)-Hybrid Coordinate ocean model (HYCOM) coupled forecast system, which is the operational hurricane forecast model currently being tested at the NOAA Environmental Modeling Center. Four numerical experiments were designed to examine the impact of assimilating underwater glider temperature and salinity data along with other conventional ocean observations. The numerical experiments consisted of: 1) no data assimilation (NODA), 2) all ocean observations except gliders assimilated (CTRL, e.g Argo profiles, XBT profiles), 3) only glider data assimilated (GLID), and 4) all ocean data available including glider data (ALL). The main finding of the numerical experiments is that through the assimilation of underwater glider observations, the pre-storm thermal and saline structures of initial upper ocean conditions are significantly improved (Figure 3a-b). The barrier layer and the associated sharp density gradient in the upper ocean, which were present during the intensification of Gonzalo (2014), are successfully represented in the ocean initial conditions only with the use of underwater glider observations (Figure 3b). The upper ocean temperature and salinity forecasts in the first 48 hours were improved by the assimilation of both underwater glider and conventional ocean observations. In addition, the assimilation of glider data showed a positive impact on the forecast of Hurricane Gonzalo. The 126-hour intensity (minimum sea level atmospheric pressure and maximum surface winds) forecast of Hurricane Gonzalo is also improved (Figure 3c-e) through the assimilation of both underwater glider data and conventional ocean observations.

Further to the north and also in October 2014, hurricanes Fay and Gonzalo hit Bermuda within a single week. BIOS deployed a glider within 2 days of the passage of Fay and it was positioned directly under the eyewall of Gonzalo, a Category-3 hurricane, as it passed overhead. The glider recorded the evolution of the cold wake created by the two storms, including a 4° C surface temperature drop, 50-meter deepening of the mixed layer, and breaking internal waves along its boundary (Figure 4). The increase in upper ocean heat content measured by the glider over the 3-month summer season of 2014 was removed in one week by these two cyclones. Each resulted in heat storage reductions of approximately 3-4 J m⁻² in the 0-250 m layer. Surface heat flux was a factor causing Hurricane Fay to intensify from a tropical storm to a hurricane as it passed Bermuda. Hurricane Gonzalo actually weakened from Category 4 to 3 as it passed over the cold wake left by Fay, just before it reached Bermuda. Turbulent mixing of surface and deeper layers contributed to the overall reduction in upper ocean heat content.



Figure

3 – (a) Temperature and (b) salinity profiles at 00 UTC October 13 2014 from the four experiments developed using HWRF-HYCOM, compared to glider observations (black line). (c) Hurricane Gonzalo track forecast. (d) Minimum sea-level pressure (center pressure), and (e) maximum wind forecasts, along with best track observations (black line).

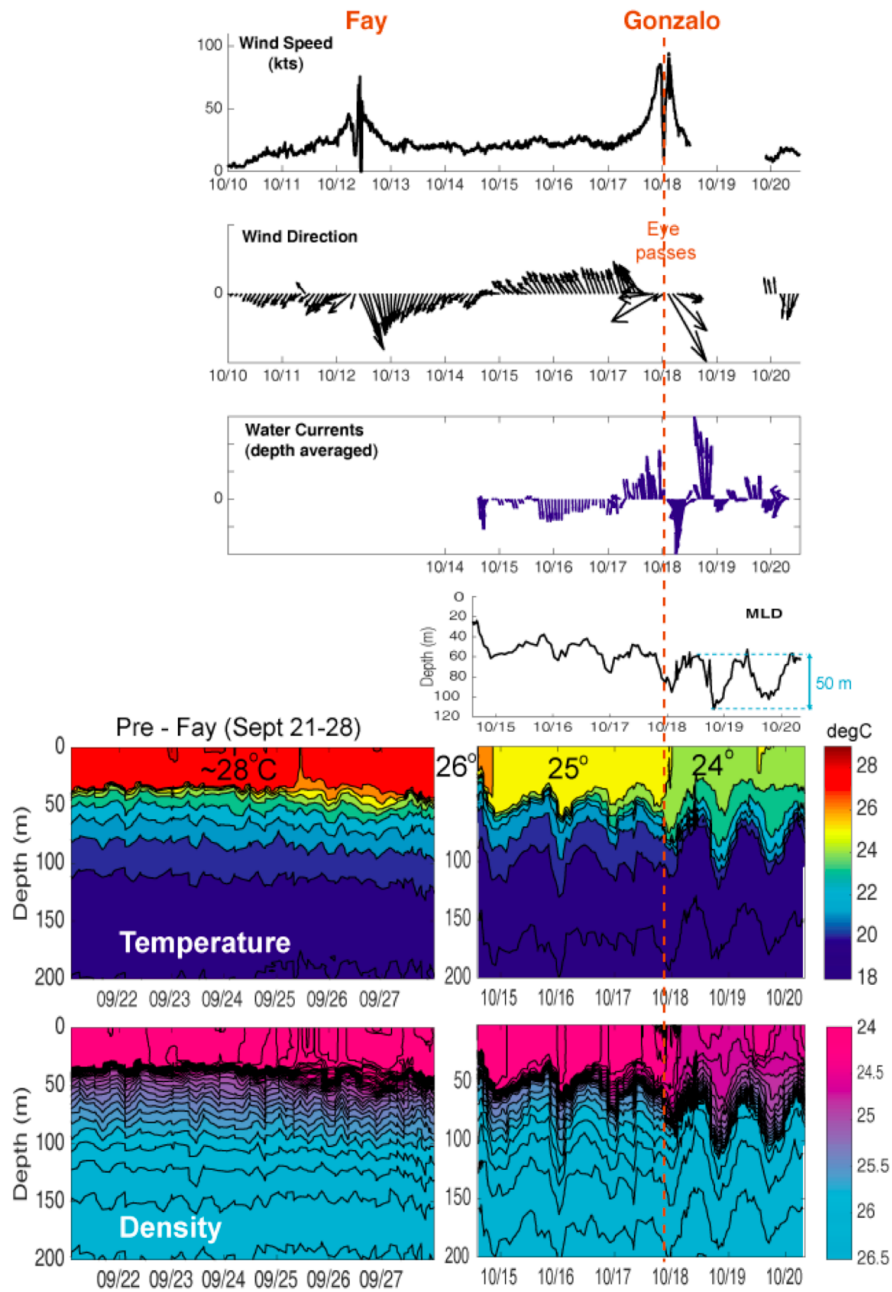


Figure 4. Atmospheric (wind speed and direction) and ocean (currents, mixed layer depth, temperature, and density) observations obtained off Bermuda by the BIOS underwater glider during the passage of hurricanes Gonzalo and Fay in 2014.

4. HURRICANES ARTHUR (2014) AND HERMINE (2016)

Errors in storm intensity forecasts during Hurricanes Irene and Sandy prompted development of the NOAA-funded TEMPESTS program in the Middle Atlantic Bight. Heavily instrumented gliders were one of three observational components in this rapid-response program, along with air-deployed profiling floats (ALAMO; see ALPS-II white paper by Jayne) and nearshore

moorings. TEMPESTS responded to two storms—Hurricane Arthur (2014) and Hurricane Hermine (2016)—that approached the Mid Atlantic coast. Hurricane Arthur moved quickly, taking only 24 hours to pass from North Carolina to northeast of Cape Cod (Figure 5a). In contrast, Hurricane Hermine stalled just south of the Middle Atlantic Bight shelf break and influenced the region for about three days before dissipating (Figure 5b). Slocum gliders were deployed by TEMPESTS partners from the Woods Hole Oceanographic Institution (Figure 5), Rutgers University, and the University of Maine two to three days before the closest approach of the storms. Mixed layers deepened and surface temperatures cooled during both storms; the magnitude of cooling observed by gliders south of Cape Cod was somewhat larger during Arthur than during Hermine (6 °C vs 4.5 °C; Figure 5c), but the longer duration of Hermine resulted in greater mixed layer deepening (approximately 30 m during Hermine vs approximately 15 m during Arthur; Figure 5d). Sediment resuspension was also notably more prolonged during and after Hermine (Figures 5e and 5f). Fast-moving Hurricane Arthur did not appear to trigger inertial oscillations over the Middle Atlantic Bight continental shelf (Figure 5g); slow-moving Hurricane Hermine did leave inertial oscillations over the shelf (Figure 5h).

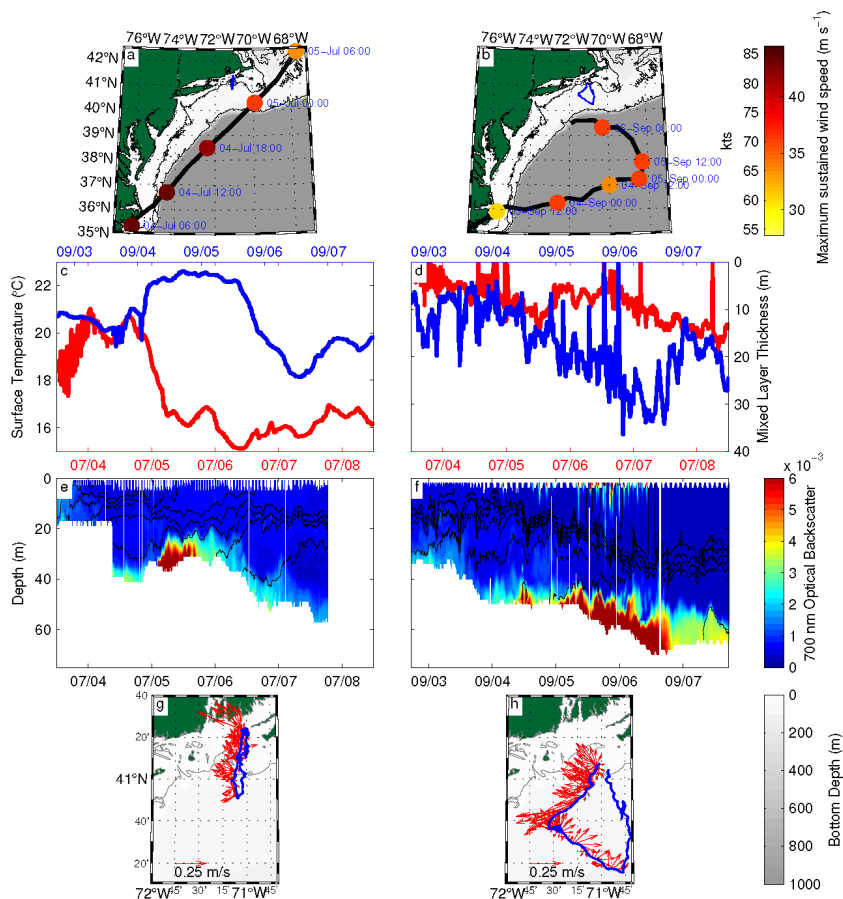


Figure 5. Observations of Hurricanes Arthur (2014) and Hermine (2016). Storm track and maximum sustained wind speed from the National Hurricane Center for (a) Arthur and (b) Hermine with WHOI glider tracks in blue (see zoomed view in g-h). Glider-based measurements of (c) near-surface temperature and (d) mixed layer depth evolution during Arthur (red) and Hermine (blue); dates in red are in 2014 for Arthur and dates in blue are in 2016 for Hermine. (e-f) Glider-based measurements of 700-nm optical backscatter, an indicator of suspended sediment, along the glider tracks during (e) Arthur and (f) Hermine. Depth averaged currents during the outbound (southward) glider transects during (g) Arthur and (h) Hermine; both storms generated westward flow over the continental shelf prior to and during storm passage; inertial oscillations are apparent on the southeasterly glider trajectory after Hermine in (h).

5. CURRENT WORK

Underwater gliders have provided full water column observations of the stratified coastal ocean response in the Atlantic Ocean and Caribbean Sea to a wide range of TCs, from early summer to mid-fall, from inshore to offshore, from perpendicular to coastline tracks, filling the critical gap for TC-ocean interaction studies in the open ocean, where they usually rapidly intensify, and on coastal areas, where impacts to populated shorelines are greatest. Within this context, the gliders from Rutgers University have focused mainly on the Mid Atlantic Bight and off the Virgin Islands, those from BIOS off Bermuda, gliders from NOAA/AOML-CARICOOS on the tropical Atlantic and Caribbean Sea, and Woods Hole on the Gulf Stream.

Though gliders have been successfully deployed in rapid-response mode ahead of storms in the Middle Atlantic Bight, the logistical hurdles for such operations are significant. With lead times typically less than one week based on forecast accuracy, gliders deployed in rapid response mode are usually deployed within two to three days of storm arrival. This short lead time prevents comprehensive measurement of pre-storm conditions (e.g., complete cross-shelf transects) and suboptimal placement of gliders during storm passage. Sustained glider operations during the storm season (as in the Caribbean and near Bermuda) are recommended so that pre-storm conditions are well sampled and operations may be planned ahead of time.

Gliders are now contributing to resolve baroclinic shallow water coastal processes, deep open ocean cooling processes, and areas in the open ocean with anomalous high upper ocean heat content. They are, therefore, providing important data to initialize numerical ocean-atmosphere coupled forecast models, and to properly identify areas that may be responsible for storm weakening and intensification. In addition, gliders provide a means to better understand the processes responsible for the rapid evolution of the ocean and its important feedback on the atmosphere during the storm.

The NOAA/AOML-CARICOOS glider network implemented in support of hurricane studies and forecasts currently includes four underwater gliders (Seagliders). During the Atlantic Hurricane

Season (June – November), two gliders are typically deployed in the tropical North Atlantic, and two are deployed in the Caribbean Sea, providing sustained observations along four repeat transects. Approximately 5,000 profiles each of temperature, salinity, dissolved oxygen, and chlorophyll are expected to be collected during each hurricane season deployment. Although surveying repeat transects, the temporal and spatial sampling coverages from these gliders have been adapted according to the operational needs to also include, for example, parking the gliders at a fixed location to obtain a time series lasting several days in order to correctly assess the impact of the hurricane force winds at a particular location.

Having gained experience and confidence with gliders, sensors, and data, BIOS is now actively identifying users and collaborators for its real-time underwater glider observations, e.g. assimilation into forecast models. To support continued science operations, the MAGIC (Mid-Atlantic Glider Initiative and Collaboration) program aims to harness and utilize the capabilities of gliders, and the unique location and facilities of BIOS, to address multi-disciplinary, hypothesis-driven marine research questions. A particular focus is on the contributions of wind-driven turbulent mixing to upper ocean heat content in the open ocean and assessing the importance of extra-tropical transitions for hurricanes.

Given the positive impact of the upper-ocean observations collected by these projects, the following recommendations are provided to further increase their contributions with the aim of improving hurricane intensity forecasts:

- To carry out the gliders observations of this network in sustained mode;
- To enhance the Caribbean Sea and tropical North Atlantic glider network by adding four to five dedicated gliders to the current NOAA/AOML-CARICOOS network, carrying out meridional sections from off-Bahamas to off-US Virgin Islands.
- To enhance the glider network in a partnership effort that includes the participation of the main glider operators in the region and new international partners;
- To develop a comprehensive underwater glider rapid response to aid in the monitoring of upper ocean heat content assessments prior to the passage of Atlantic hurricanes;
- To carry out numerical Observing System Simulation Experiments (OSSEs) to assess the impact of glider data on Atlantic hurricane intensity forecasts and to determine the optimal and most cost-effective locations for glider observations; and
- To include additional sensors in the gliders to enable multi-disciplinary studies geared towards assessing the impact of hurricanes on ecosystems, carbon dioxide fluxes, fisheries, etc.

ACKNOWLEDGEMENTS

The NOAA/AOML component of this work was originally funded by the Disaster Relief Appropriations Act of 2013, also known as the Sandy Supplemental, and is currently funded by the NOAA research grant NA14OAR4830103, by NOAA's Atlantic Oceanographic and Meteorological Laboratory, and by CARICOOS (Caribbean Coastal Observing System), and is

also supported by NOAA Integrated Ocean Observing System (IOOS), and by the NOAA National Data Buoy Center. The WHOI component of this work was supported by NOAA through the Cooperative Institute for the North Atlantic Region (NA13OAR4830233) and the WHOI Summer Student Fellowship Program.

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