Final Report

2022 Atlantic Hurricane Saildrone Mission

July 16 – November 6, 2022

Left: Saildrone 1032's deployment near St. Petersburg, Florida in August 2022.
Right: Picture taken by Saildrone 1078 in Hurricane Fiona in the North Atlantic on September 22, 2022.

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Note: All results reported in this document are subject to revision after post-mission data calibrations and other quality-control procedures have been completed. Initial data from all saildrones is available from https://www.pmel.noaa.gov/saildrone-hurricane/index.html.

OVERVIEW

The NOAA Atlantic Hurricane Saildrone Mission aims to collect direct measurements of the upper ocean and near-surface atmosphere in the western tropical/subtropical Atlantic Ocean, Caribbean Sea, and Gulf of Mexico during the peak of the Atlantic hurricane season (August-October). During the 2022 mission, data were collected continuously from seven Saildrone autonomous uncrewed surface vehicles (USVs) and was transmitted in near-real-time to global weather forecast centers through the Global Telecommunication System (GTS), with the goal of improving operational hurricane situational awareness and intensity forecasts. The Saildrone USVs are propelled by the wind, and their sensors and instruments are powered by solar and wave energy. Five of the Saildrone USVs were coordinated with underwater gliders to acquire nearly collocated and continuous measurements of the upper ocean and near-surface atmosphere. Six of the Saildrone USVs were directed into the paths of two different tropical cyclones: Hurricanes Fiona and Ian, both with a maximum intensity of category 4 on the Saffir-Simpson scale. Data from three of the Saildrone USVs in Hurricanes Fiona and Ian were used by NOAA's National Hurricane Center in its forecast advisories.

Introduction

Improving the accuracy and ultimate value of NOAA's operational hurricane forecasts requires more complete real-time knowledge of atmospheric and oceanic conditions and more realistic representation of key physical processes in hurricane forecast models. The NOAA Atlantic Hurricane Saildrone missions seek to address these needs through the deployment of Saildrone USVs (hereafter "saildrones") during the peak of the Atlantic hurricane season. These surface vehicles continuously measure the near-surface atmosphere (temperature, humidity, wind velocity, solar radiation, and pressure) and upper ocean (sea surface temperature, salinity, oxygen, chlorophyll, surface and subsurface ocean currents, wave height and period) and transmit one-minute averaged data in near-real-time to global weather forecast centers. Coordination with underwater glider observations provides collocated measurements of the upper ocean and atmosphere. The saildrones are directed opportunistically to measure ahead of and inside of any approaching tropical cyclone. Whenever possible, saildrone measurements in tropical cyclones are coordinated with other elements of NOAA's Hurricane Field Program to provide valuable collocated observations of the ocean and atmospheric boundary layer. The saildrone measurements are also valuable for quantifying air-sea heat and momentum fluxes and the ocean's response to extreme wind forcing, and for assessing hurricane model errors.

Saildrones are USVs propelled by wind and powered by solar energy for instrumentation and navigation. They are equipped with sensors that measure atmospheric and oceanic variables near the air-sea interface. Launched and retrieved from seaports and piloted remotely, saildrones can sample continuously for up to 12 months. Seven extreme weather saildrones were deployed for the 2022 hurricane observations. Their sensor configurations are the same as the commonly used model (Explorer) except the height of certain sensors mounted on the wings. Two of the seven saildrones were equipped with additional shortwave Delta-T Devices SPN-1 pyranometers and longwave Eppley PIR pyrgeometers. Information on the sensors used in the 2022 deployment is given in Table 1.

Table 1 Main meteorological and oceanic sensors on extreme weather saildrones used in the 2022 hurricane observations mission. Asterisks mark the variables transmitted to GTS in near real time.

Sensor	Variable (1-minute and 5-minute averages available in near real-time)	Manufacturer's Accuracy	Height (above sea surface)	Sampling Frequency and Default Schedule (changeable in real time as needed)
Anemometer Gill Windmaster 3D Utrasonic 20Hz	wind speed and direction*	±1.5%	3.5 m	20 Hz always-on
Light sensor Li-Cor Li-192SA	photosynthetically active radiation	±5%	2.6 m	1 Hz always-on
Humidity and temperature probe Rototronic HC2-S2	air temperature and relative humidity*	±0.8%	2.3 m	1 Hz always-on
IR Pyrometer Heitronics CT15.10	skin sea surface temperature	± (0.5 C + 0.7% target-housing T)	2.3 m	1 Hz always-on
Dual GPS-aided IMU VN300	surface wave height and period*	heave: ±5% or 5 cm	0.3 m	20 Hz always-on
Barometer Vaisala BAROCAP PTB210	surface pressure*	± 0.15 hPa	0.2 m	1 Hz always-on
Sea-Bird SBE 63	dissolved oxygen	± 2% saturation	-1.5 m	1 Hz 12 bursts/5-min.
CTD Seabird SBE37	water temperature and salinity*	T: ±0.0002 C C: ± 0.003 mS/cm	-1.5 m	1 Hz 12 bursts/5-min.
Fluorometer Wetlabs ECO FL-S-G4	chlorophyll	NA	-1.8 m	1 Hz 12 bursts/1-min.

ADCP Teledyne Workhorse 300 kHz	ocean current (upper 100 m)	0.5 cm/s	-1.9 m	1 Hz always-on
Pyranometer Delta-T SPN1	downward shortwave radiation	± 5%	2.8m	5 Hz always-on
Pyrgeometer Eppley PIR	downward longwave radiation	5 W/m^2	0.7m	1 Hz always-on

There is preliminary on-board data quality control (QC) including motion corrections of the wind relative to fixed ground taking into consideration the pitch, roll and motion of the vehicles. Once data are received by PMEL, no automated QC is performed before the data are placed onto the GTS. Data provided to operational centers through the GTS are quality controlled by the centers, regardless of the quality control status of the data before dissemination. In-line fully automated data QC functionality is now being developed with an expectation of being implemented in 2023. This data QC procedure will include automated quality assessment and flagging of data by applying machine learning techniques to provide an initial assessment of the data quality and identifying and treating missing, suspicious, or erroneous data resulting from malfunction of sensors or data transmission. After the saildrone vehicles are retrieved, high-resolution data from all onboard sensors are downloaded and delivered to PMEL as files containing 20 Hz, 4 Hz or 1 Hz observations (Table 1). High resolution data for short periods can be telemetered in near real-time as needed.

Saildrone operational domain selection

The top priority of the mission was to obtain measurements inside hurricanes. Saildrone operational domains were selected based on historical tracks and intensities of tropical cyclones. We first calculated the odds of each 1^{o} x 1^{o} grid box experiencing tropical storm (TS)-force winds (>18 m s^{-1}) during August-October, using 2000-2019 data from version 2 of the Atlantic Hurricane Database (Landsea and Franklin, 2013). A radius of TS-force winds (R34) of 191 km was used, based on the mean R34 for the Caribbean and North Atlantic (Quiring et al. 2011). Next, we estimated that our modified short-wing saildrones would be able to travel 50 km day^{-1} about 50% slower than an Explorer saildrone with a taller wing (Meinig et al. 2019). Assuming 100% accurate four-day track forecasts gives a 200-km search radius at each location. In other words, if the edge of the TS-force wind field was predicted to pass within 200 km of a saildrone's location, the saildrone would travel fast enough to reach the wind field. The odds of a saildrone at any location experiencing at least TS-force winds were then calculated from the number of times an R34 wind field passed within 200 km of that location in August-October of each year (2000-2019). Each year was then assigned a value of zero or one, depending on whether the count for that year was zero or greater than zero, respectively, and the sum of the values was divided by the total number of years (20). The resulting probabilities range from less than 20% south of Cuba to close to 80% in the central and western subtropical North Atlantic (colors in Fig. 1).

The map of probabilities shows the odds that a saildrone at a given location will be able to experience TS-force winds during August-October. We extended the analysis to calculate the odds that at least one of seven saildrones, each at a different location, would experience TS-force winds. We decided on a set of seven areas that would give us >95% chance of at least one saildrone experiencing TS-force winds (boxes in Fig. 1). The second-highest priority for the saildrone mission was to obtain nearly collocated and simultaneous observations from underwater gliders. Two gliders were already planned to perform repeat transects north of Puerto Rico up to about 22°N during June-November, and there were two gliders planned south of Puerto Rico extending to about 16°N. We therefore deployed one saildrone in each of those areas (Fig. 1). A series of glider deployments was also planned in the near-coastal region of the southeastern U.S. during the hurricane season, so one saildrone was deployed in that area. Planned glider deployments in the Gulf of Mexico (green shapes/lines in Fig. 1) also informed our saildrone operational areas there. Finally, because of the saildrones' shorter wings and slower sailing speeds, we attempted to avoid areas with strong ocean currents (pink contours in Fig. 1), such as the Gulf Stream and Loop Current. Near real-time glider locations were automatically provided to the mission team during the missions with the aim to coordinate with saildrone-glider observations collocated within a 10 km radius.

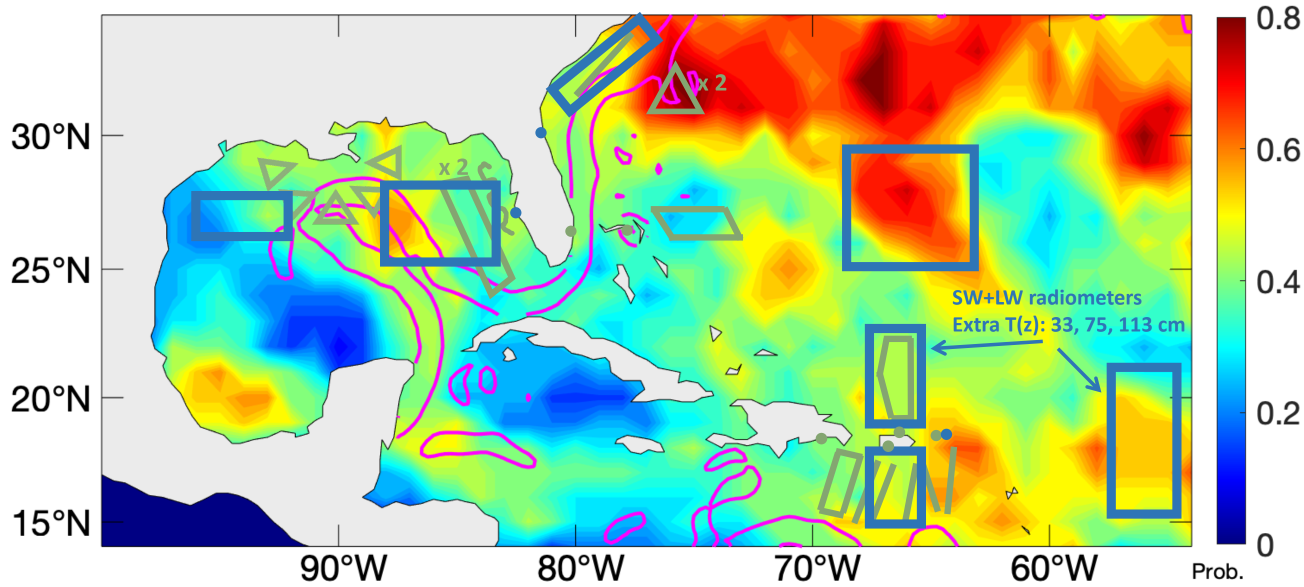

Figure 1 Planned 2022 saildrone operational domains (blue boxes). Also shown are planned underwater glider tracks (green lines), saildrone deployment locations (blue dots), and glider deployment locations (green dots). Colored shading indicates probability of tropical storm-force winds during August-October, based on tropical cyclone data during 2000-2019. Pink contour line indicates surface currents of 50 cm s^{-1} on September 15, 2021.

Saildrone mission summary

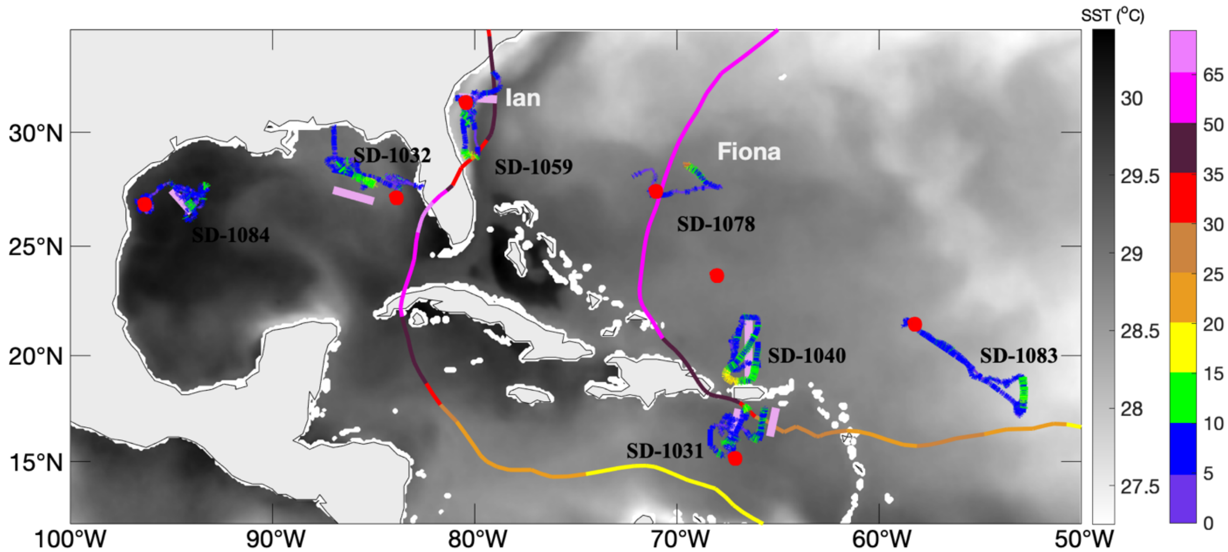

Figure 2 Tracks of saildrones (squiggly colored lines) and their hourly-averaged wind speed measurements (color scale on the right in m s^{-1}), underwater gliders (straight pink lines), and tropical cyclones that passed close to a saildrone (smooth lines: colors indicate maximum 1-min sustained wind speed using the color scale on the right) during the 2022 hurricane season. Red dots indicate locations of NDBC surface meteorological buoys that were compared with saildrone data.

1 Major accomplishments

1. Two major hurricanes were observed by six different saildrones, twice near their eyewalls. Fiona was observed by four saildrones from when it was first named a tropical storm to when it became a category 4 hurricane. Ian was observed as it made landfall on the west coast of Florida and again after it crossed Florida into the Atlantic Ocean (see Fig. 2).
2. Selected observations (air temperature, humidity, pressure, wind direction and speed, ocean temperature and salinity, wave height and period) were submitted in real time to the Global Telecommunication System (GTS) for operational environmental forecasts.
3. Observations were used by the National Hurricane Center in their advisories.
4. Coordinations were made between saildrones and underwater gliders 10 times with a total of 145 days of collocated measurements (see Fig. 2).
5. Saildrones made comparisons with moored buoys 18 times with a total of 20 days of collocated measurements.

2 Summary of key observations in Hurricanes Fiona and Ian

As shown in Fig. 2, six different saildrones acquired measurements from Hurricanes Fiona and Ian. Key wind velocity and barometric pressure readings from the saildrones in Fiona and Ian are presented in Tables 2 and 3, respectively.

Table 2 Key measurements from saildrones in Hurricane Fiona. Wind speed is averaged over one minute and wind gust is the maximum 3-second average in each 1-minute interval.

	SD-1083	SD-1031	SD-1040	SD-1078
Maximum wind speed (kt)	**38.4**	**51.4**	**47.0**	**68.1**
Direction (deg. from north)	93.2	31.9	82.9	140.6
Latitude	17.94	17.49	18.78	28.56
Longitude	-52.85	-66.51	-67.19	-69.51
Date/time (UTC)	9/15/22 11:15	9/18/22 14:35	9/18/22 18:59	9/22/22 13:33
Maximum wind gust (kt)	**45.8**	**66.3**	**59.4**	**94.1**
Direction (deg. from north)	93.2	219.9	84.0	146.9
Latitude	17.94	17.48	18.78	28.57
Longitude	-52.85	-66.59	-67.19	-69.52
Date/time (UTC)	9/15/22 11:15	9/18/22 16:45	9/18/22 19:22	9/22/22 13:48
Minimum pressure (hPa)	**1011.7**	**987.3**	**1004.1**	**972.1**
Latitude	18.14	17.48	18.78	28.69
Longitude	-52.85	-66.57	-67.21	-69.50
Date/time (UTC)	9/15/22 6:18	9/18/22 16:06	9/18/22 20:02	9/22/22 15:44

Table 3 Key measurements from saildrones in Hurricane Ian. Wind speed is averaged over one minute and wind gust is the maximum 3-second average in each 1-minute interval.

Maximum wind speed (kt)	SD-1032	SD-1059
Direction (deg. from north)	**35.4**	**56.4**
Latitude	8.9	335.6
Longitude	27.77	29.00
Date/time (UTC)	-84.99	-80.07
Maximum wind gust (kt)	9/29/22 1:00	9/29/22 23:38
Direction (deg. from north)	**43.0**	**73.8**
Latitude	13.2	336.0
Longitude	27.76	29.00
Date/time (UTC)	-84.97	-80.07
Minimum pressure (hPa)	9/29/22 1:28	9/29/22 23:35
Latitude	**1009.1**	**989.3**
Longitude	27.84	29.03
Date/time (UTC)	-85.14	-80.20
	9/28/22 21:14	9/29/22 20:07

2.1 SD-1083 (Fiona)

Saildrone 1083 was in an area to the north of the predicted track of Tropical Storm Fiona on September 14, prior to the storm's arrival (Fig. 2). SD-1083 was directed toward the south to intercept Fiona and ended up in the strongest part of the storm, recording maximum 38 kt with gusts to 46 kt (Table 2). Maximum significant wave height was 6 m (Fig. 3). All sensors on SD-1083 were set to record continuously for the storm, and there are no significant data gaps (Fig. 3). A summary of SD-1059's speed over ground as a function of wind speed is shown in Fig. 4, color-coded by surface pressure. As expected, vehicle speed increases in general as wind speed increases.

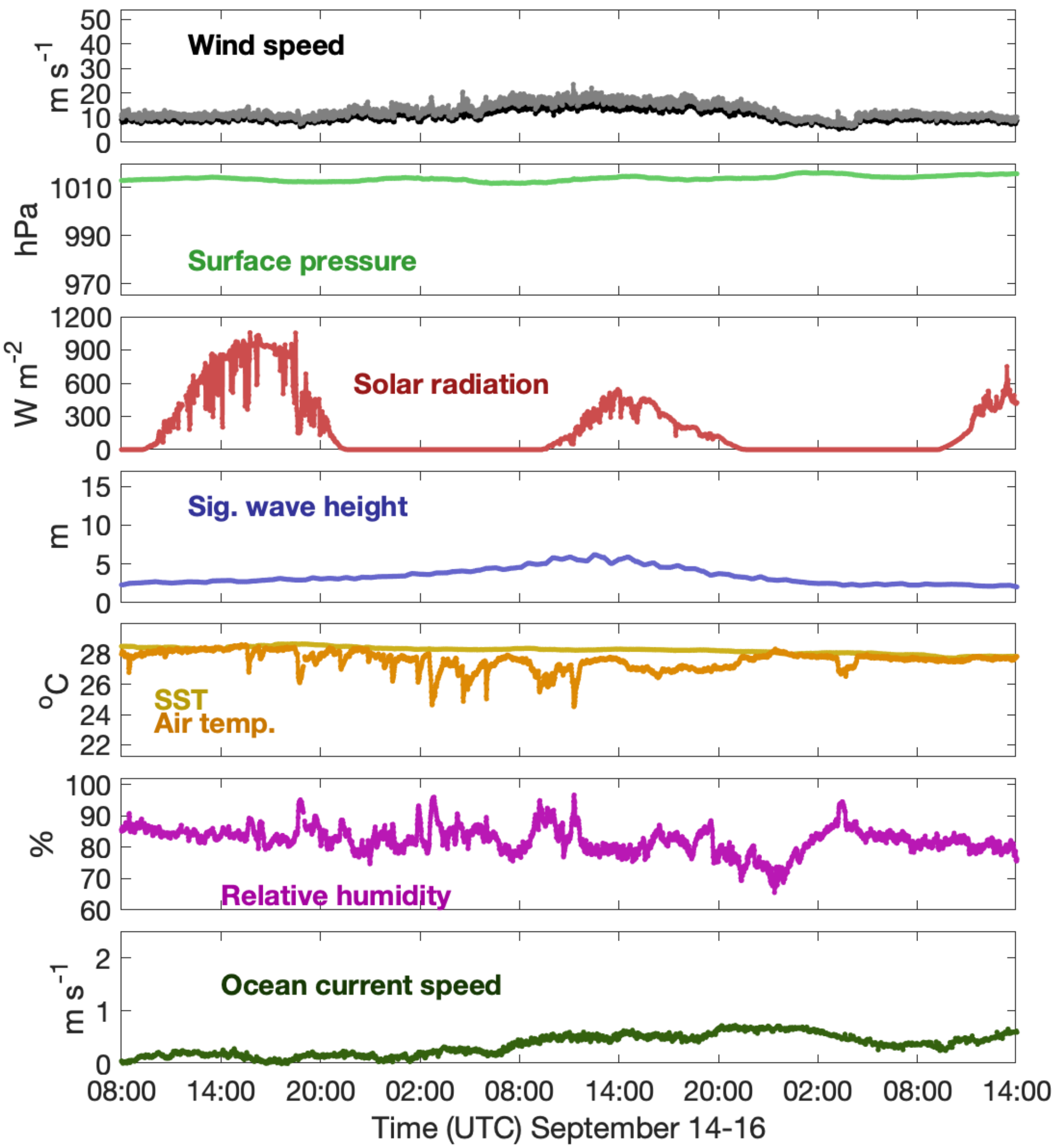

Figure 3 Key measurements (1-minute averages for most variables) from SD-1083 in Tropical Storm Fiona.

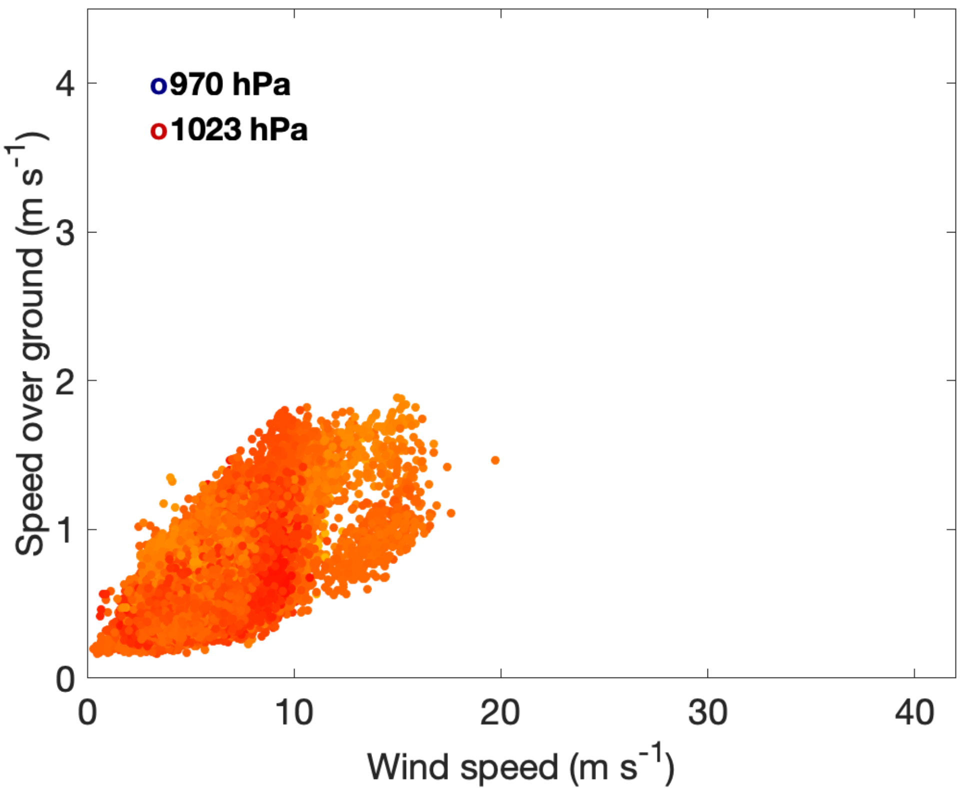

Figure 4 Scatterplot of SD-1059's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

2.2 SD-1031 (Fiona)

Saildrone 1031 was located south of Puerto Rico (17°N, 66.5°W) as Tropical Storm Fiona approached from the east during September 15-18 (Figs. 2, 5). We directed SD-1059 to the north with glider SG-610 to intercept the storm. During September 17-18, very little additional adjustments to SD-1059's position were needed. We positioned SD-1031 to go through the center of the storm while SG-610 continued on its planned track toward the north. SG-610 ended up only a few miles north of SD-1031 as Fiona passed over both vehicles and intensified to a category 1 hurricane (Fig. 5). Evidence of the passage of Fiona's eye over SD-1031 can be seen in the wind speed time series (Fig. 6), which shows a maximum 1-minute wind speed of 51 kt (25 m s^{-1}) that is preceded by a period of more than an hour with wind speed less than 20 kt (10 m s^{-1}). There is also an increase in surface solar radiation inside the eye (Fig. 6). Nearly collocated subsurface temperature and salinity measurements from SG-610 show significant near-surface cooling and increase in near-surface salinity as the strongest winds of Fiona passed over it (Figs. 7, 8). Above wind speeds of about 15 m s^{-1}, the speed over ground of SD-1031 does not vary much with wind speed (Fig. 9). This is because very little pre-storm vehicle movement or positioning were required. Interestingly, the vehicle's speed remained high in the storm's eye, where winds were weak (blue dots in Fig. 9), likely due to strong near-surface currents that pushed SD-1031 to the west.

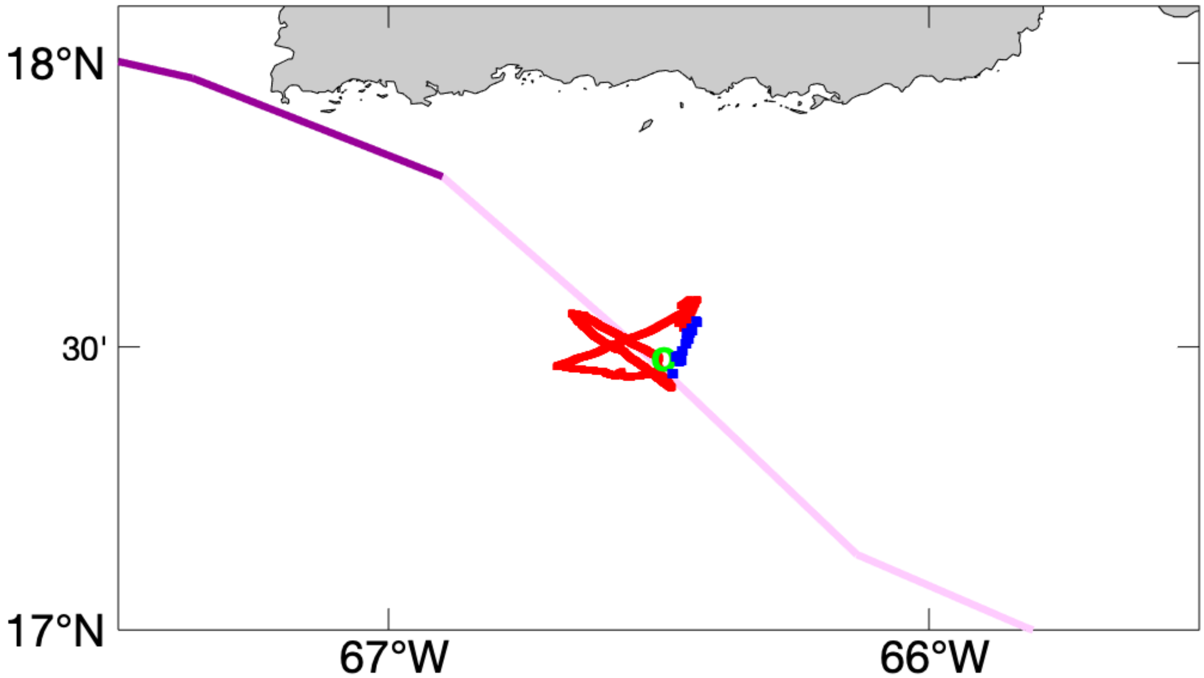

Figure 5 Track of Tropical Storm (light purple) and Hurricane (dark purple) Fiona south of Puerto Rico. Blue line shows path of SG-610 northward during 15:00 UTC September 17 through 21:00 UTC September 19. Red line shows path of SD-1031 during the same time period, with green circle indicating the initial position.

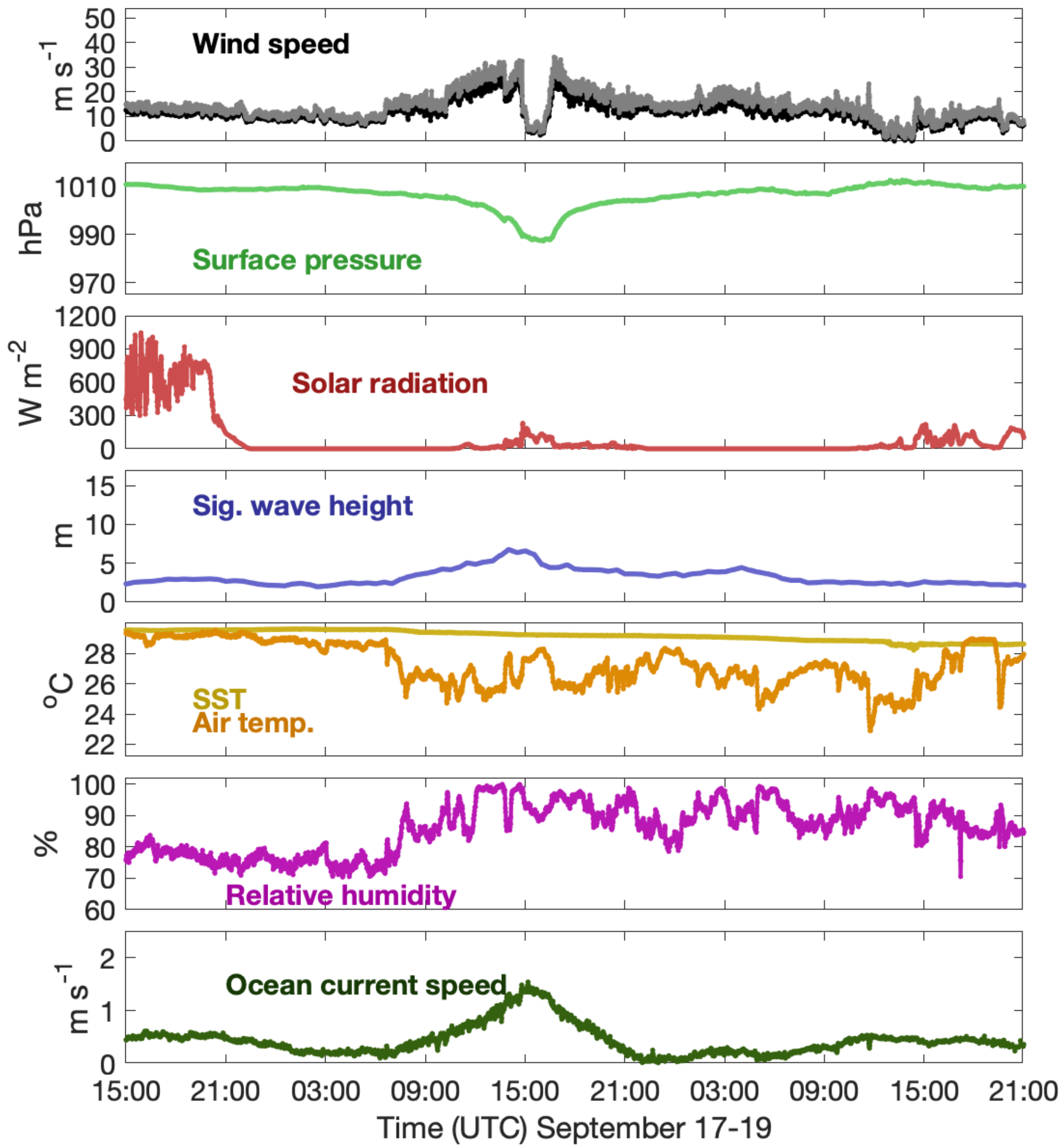

Figure 6 Key measurements (1-minute averages for most variables) from SD-1031 in Hurricane Fiona.

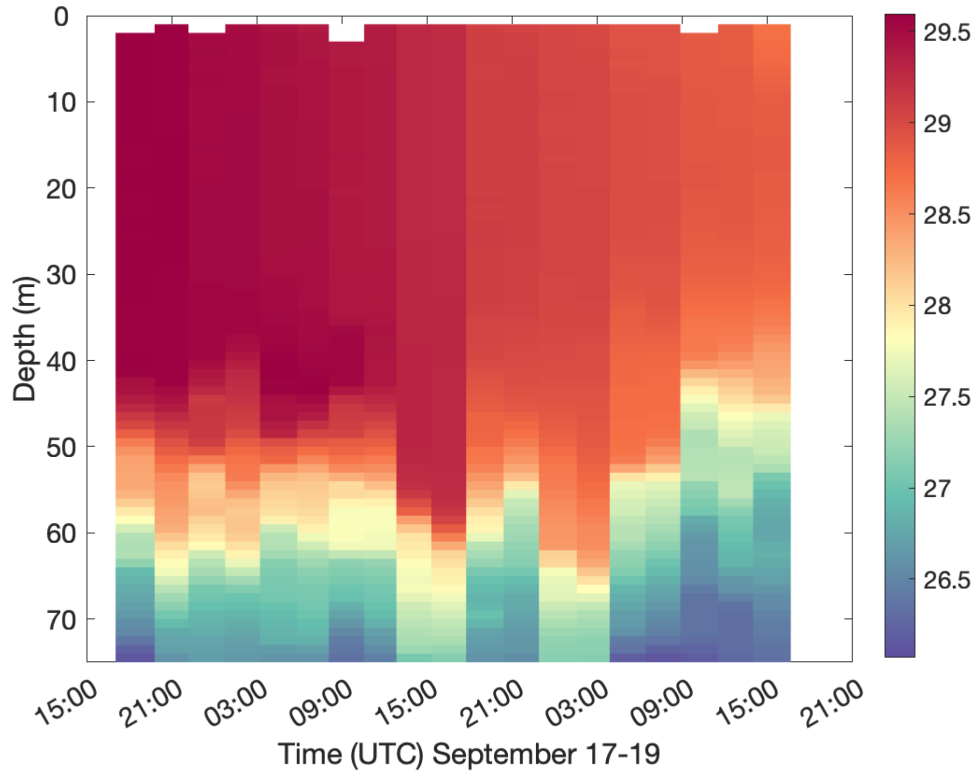

Figure 7 Profiles of ocean temperature acquired from glider SG-610 as Hurricane Fiona passed over it.

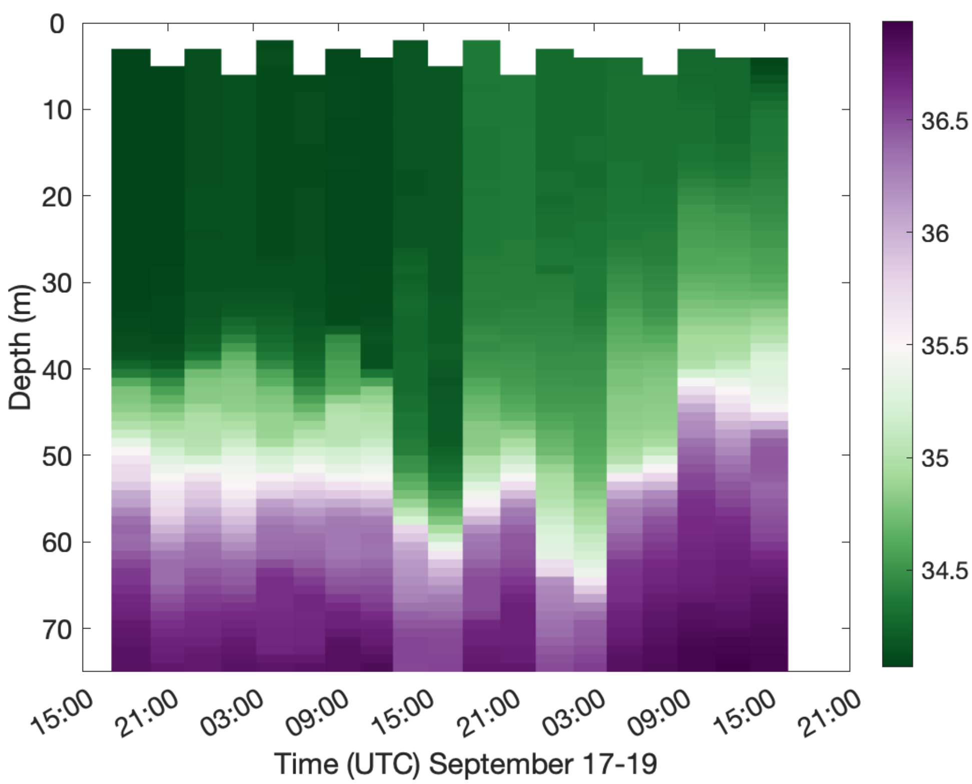

Figure 8 Profiles of ocean salinity acquired from glider SG-610 as Hurricane Fiona passed over it.

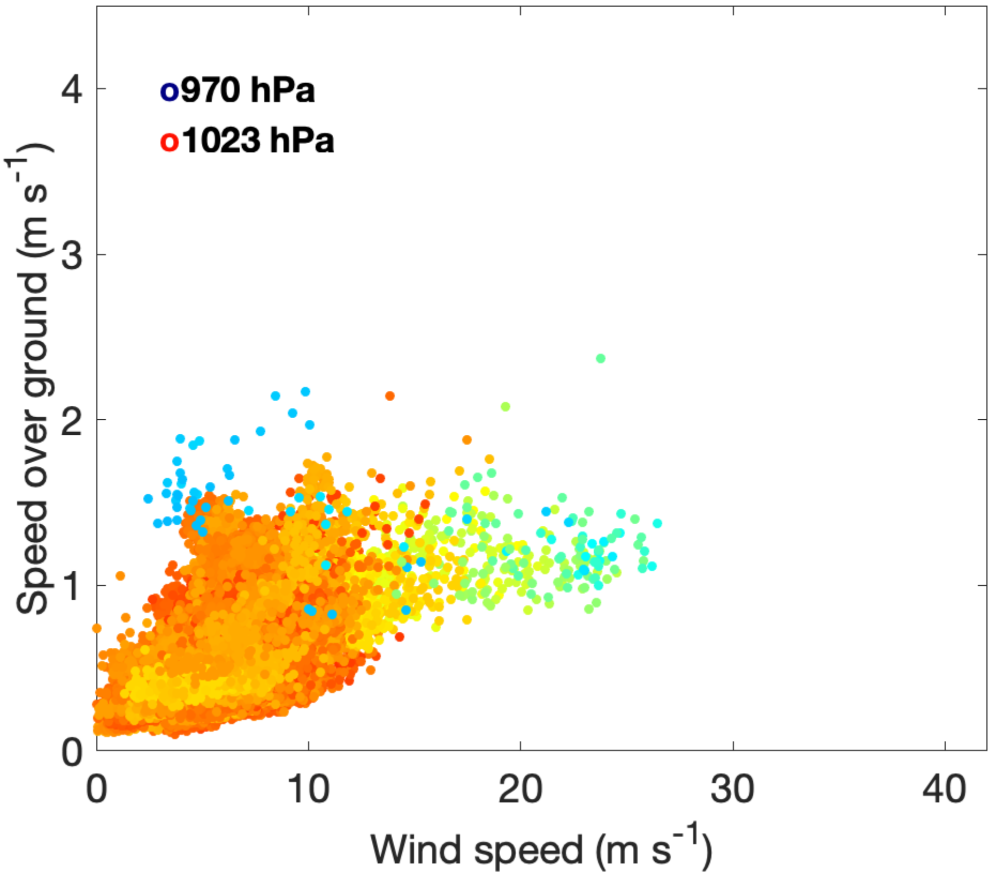

Figure 9 Scatterplot of SD-1031's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

2.3 SD-1040 (Fiona)

Saildrone 1040 was following an underwater glider northward to the north of Puerto Rico when forecasts around 18:00 UTC September 15 showed that Tropical Storm Fiona was likely to pass close to it. At that time, SD-1040 was located at about 20.7°N, 66°W. We routed the vehicle southward and then south-southwestward in an attempt to intercept Fiona. SD-1040 drifted westward in the surface currents and winds from Fiona and ended up about 80 km north of the storm's center at about 21:00 UTC September 18. SD-1040 measured tropical storm-force winds (18 m s^{-1}) for approximately 13 hours during 17:00 UTC September 18 until 06:00 UTC September 19 (Fig 10). In contrast to the vehicle speed of SD-1031, which levels off at about 15 m s^{-1} wind speeds (Fig. 9), the speed of SD-1040 continues to increase for wind speeds up to 20 m s^{-1} (Fig. 10). The difference is due to our active routing of SD-1040 toward the south to intercept Fiona as the storm approached and winds increased. However, note that rough ocean conditions and continued westward drift of SD-1040 toward Dominican Republic territorial waters necessitated and end to active routing as winds peaked. This is visible in the cluster of yellow dots in Fig. 10 around speeds over ground of about 1.5 m s^{-1}.

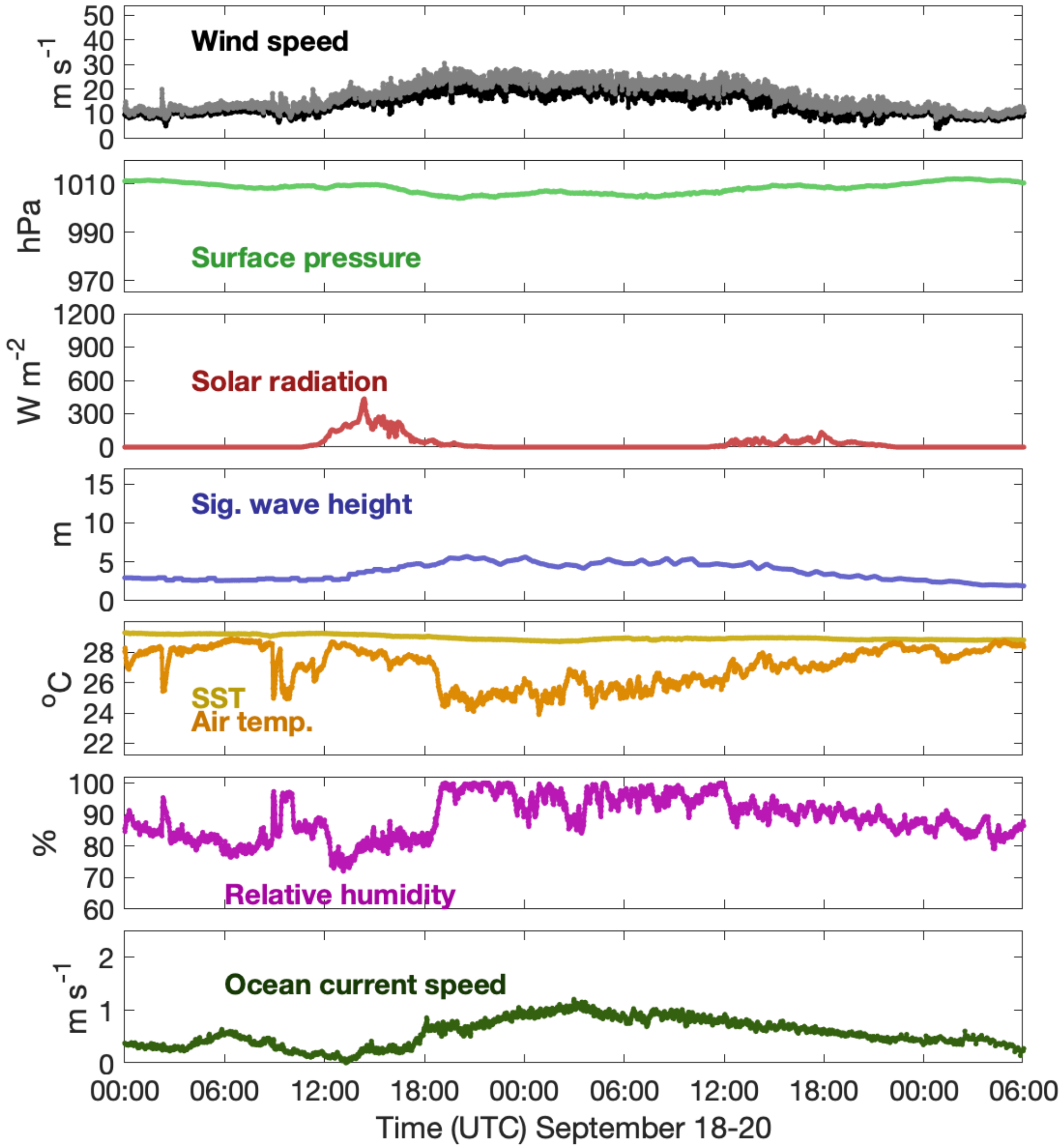

Figure 10 Key measurements (1-minute averages for most variables) from SD-1040 in Hurricane Fiona.

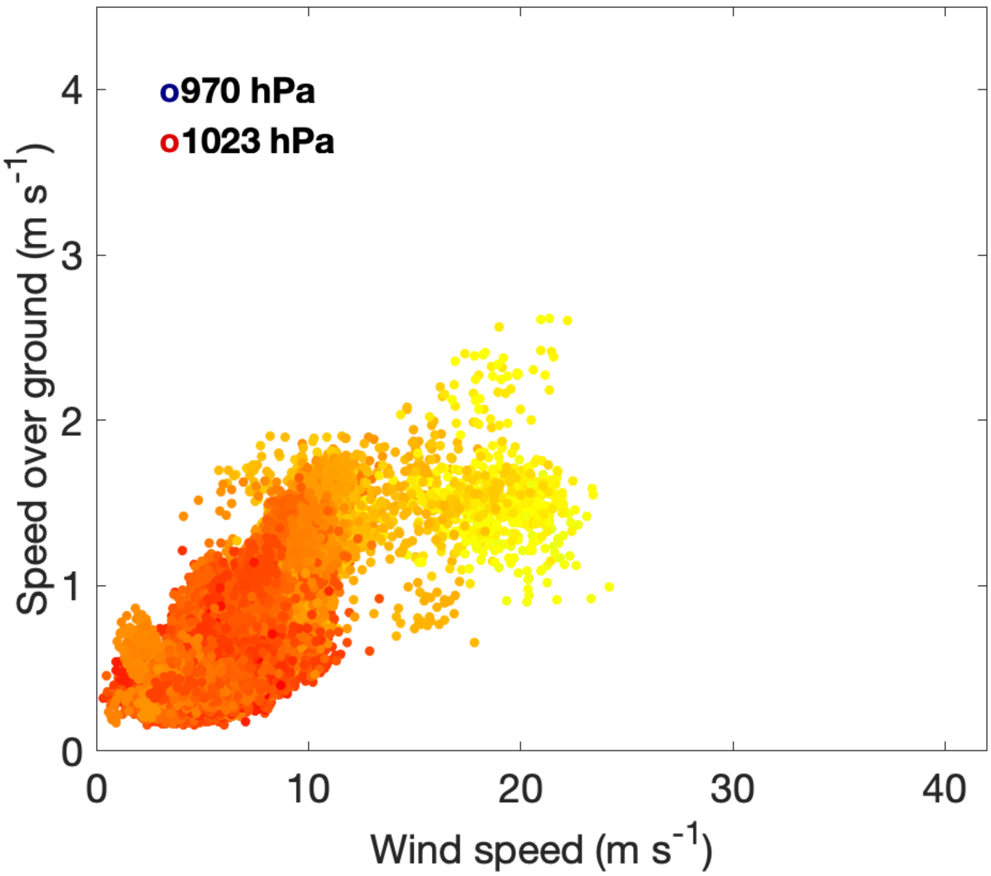

Figure 11 Scatterplot of SD-1040's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

2.4 SD-1078 (Fiona)

For Saildrone 1078, prior to 10:00 UTC September 19 we kept it near 27.6°N, 67.9°W in anticipation of the arrival of Hurricane Fiona. Our goal was to keep SD-1078 east of the easternmost likely path of Fiona, based on the ensemble of hurricane track forecasts. This would ensure that SD-1078 was on the right (strongest) side of the storm as it passed. After 10:00 UTC September 19, it became clear that Fiona would take a more western track, so we directed SD-1078 on a westward path. Beginning 05:00 UTC September 20, we determined that the best strategy for intercepting the storm would be to take SD-1078 on a west-northwestward trajectory, since Fiona was predicted to curve from a northward to northeastward trajectory as it approached SD-1078. At 19:00 UTC September 20, we changed to a more aggressive north-northwestward path for SD-1078 after considering updated track and intensity forecasts and the likely forward speed of SD-1078. That trajectory was maintained until 08:00 UTC September 22, when tropical storm-force winds and significant wave heights of 7 m necessitated stopping the vehicle and directing it into the wind. Unfortunately, this left SD-1078 about 50 km east of the predicted location of the storm's center, just outside the eyewall.

As the strongest winds and largest waves approached, SD-1078's wing sensors (air temperature, relative humidity, solar radiation, wind) failed (Fig. 12). At that point, significant wave height was more than 15 m and there were sustained hurricane-force winds (35 m s^{-1}). The details of the wing/sensor failure are unclear because the saildrone has not yet been recovered as of the writing of this report, though it is getting closer to Bermuda. As SD-1078 chased Fiona, winds approached 20 m s^{-1} and its speed over ground increased to up to 2.5 m s^{-1} (Fig. 13). However, as mentioned previously, for safety of the vehicle, its forward motion was stopped when winds were close to 20 m s^{-1}, resulting in a leveling off of forward speed as winds continued to increase and pressure dropped (Fig. 13).

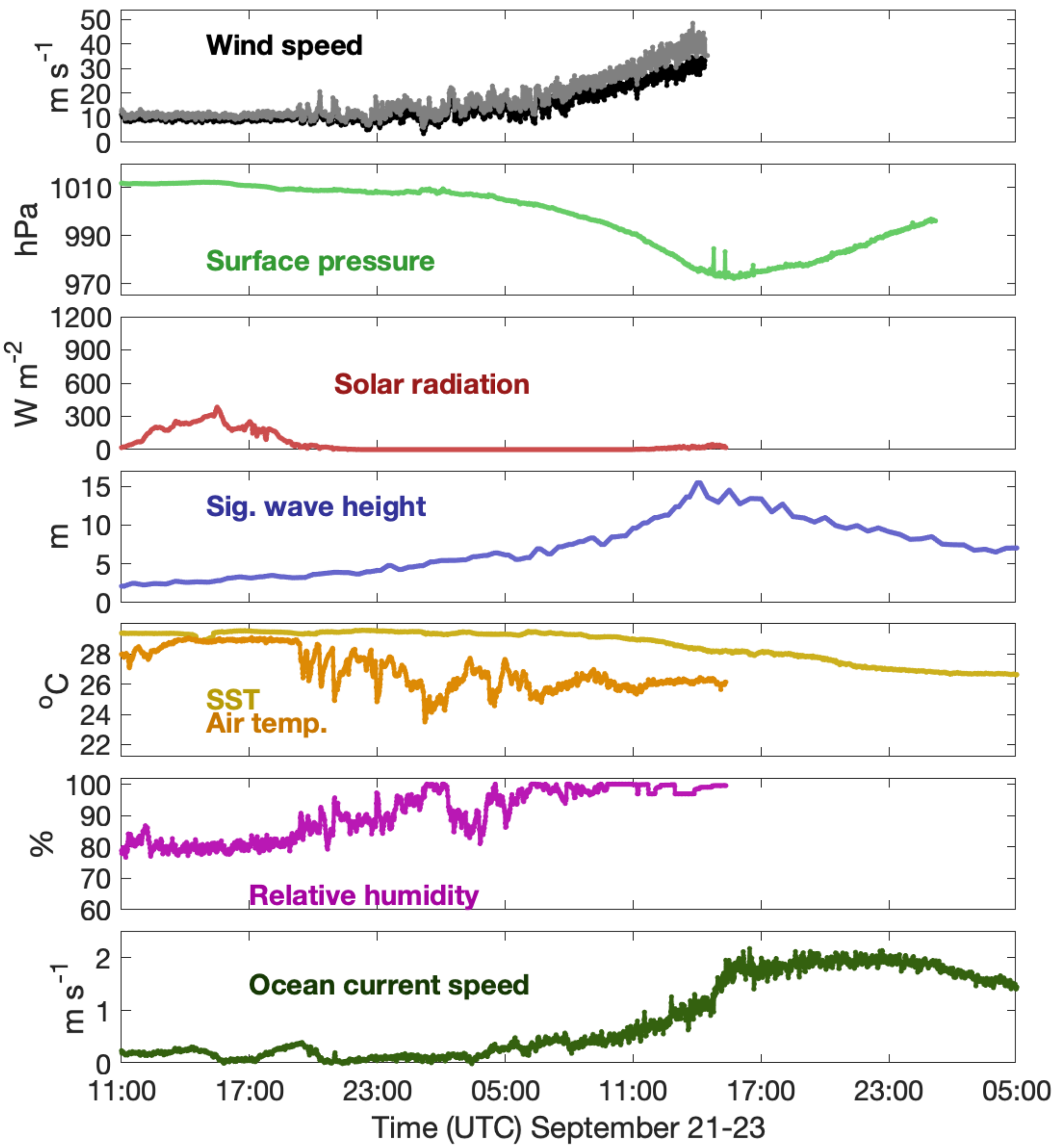

Figure 12 Key measurements (1-minute averages for most variables) from SD-1078 in Hurricane Fiona.

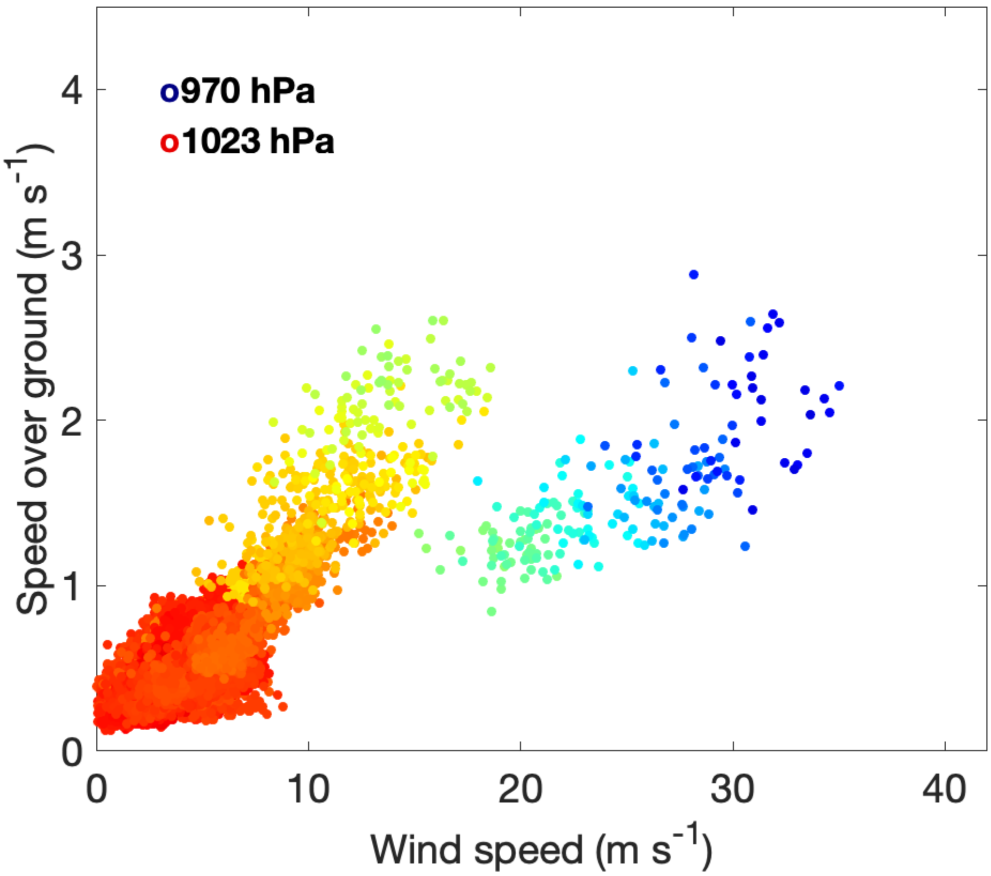

Figure 13 Scatterplot of SD-1078's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

2.5 SD-1032 (Ian)

At about 22:00 UTC September 21, there was confidence that a disturbance in the Caribbean was predicted to instensify rapidly and track northward into the eastern Gulf of Mexio as Hurricane Ian. At that time, SD-1032 was located in the northeastern Gulf at about 28.4^{o}N, 87^{o}W, acquiring measurements with an Argo float. We immediately put SD-1032 on an east-southeast trajectory to get it closer to the predicted path of the storm. However, due to weak winds and unfavorable surface currents, SD-1032's progress was very slow: it went about 50 km to east in 5 days. In addition, the track forecast for Ian continued to shift southward, meaning there was no chance that SD-1032 could intercept it. We continued to direct SD-1032 to the east-southeast in the hope that the storm would track farther west than forecast and that it might at least get into tropical storm-force winds. Fortunately, SD-1032 did end up on the outer edge of Hurricane Ian's tropical storm-force winds, with a maximum 1-min. wind speed of 35 kt (17 m s^{-1}; Table 3, Fig. 14). The maximum forward speed of SD-1032 as Hurricane Ian approached was about 2 m s^{-1} in winds of 15-17 m s^{-1} (Fig. 15).

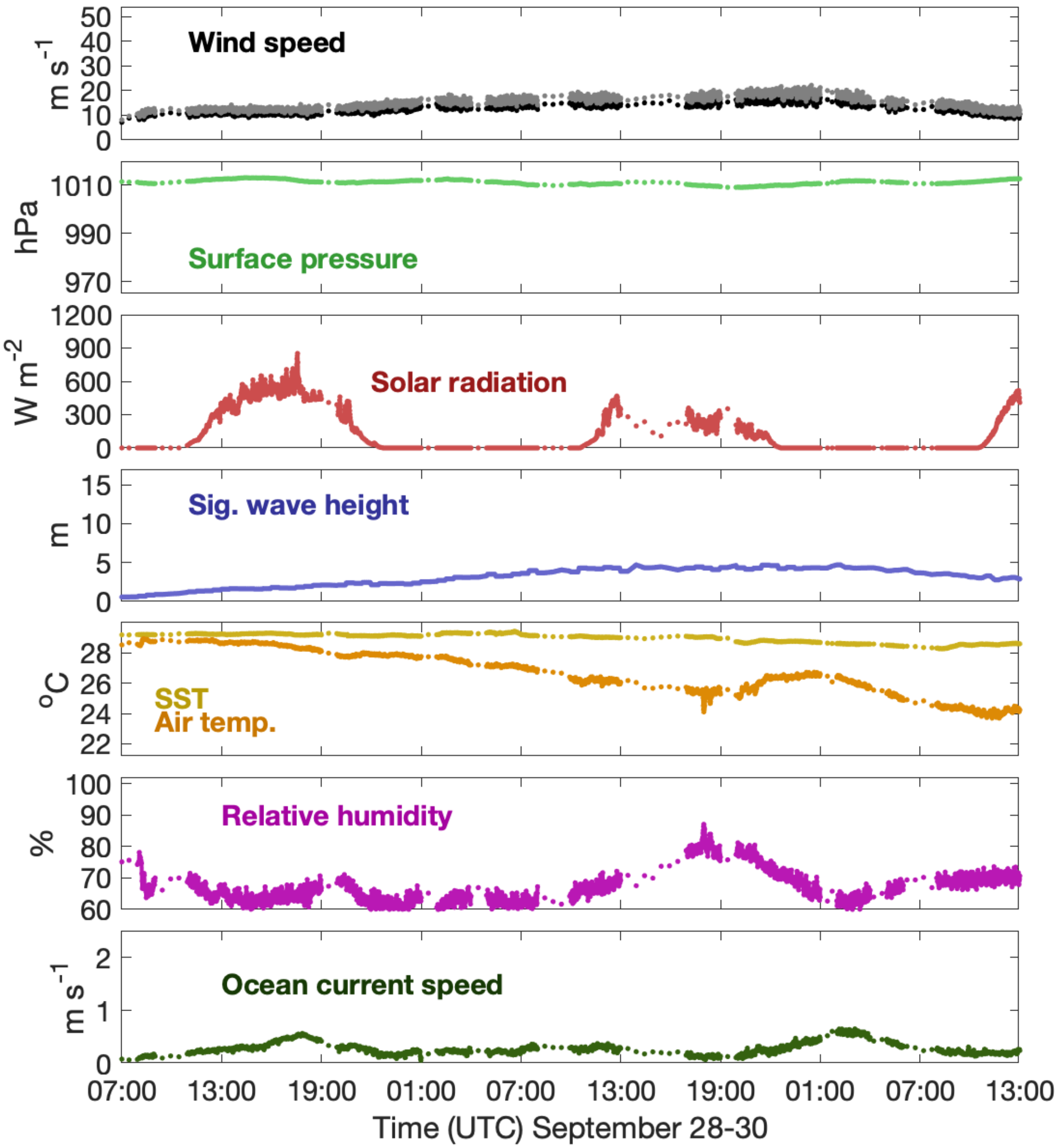

Figure 14 Key measurements (1-minute averages for most variables) from SD-1032 in Hurricane Ian.

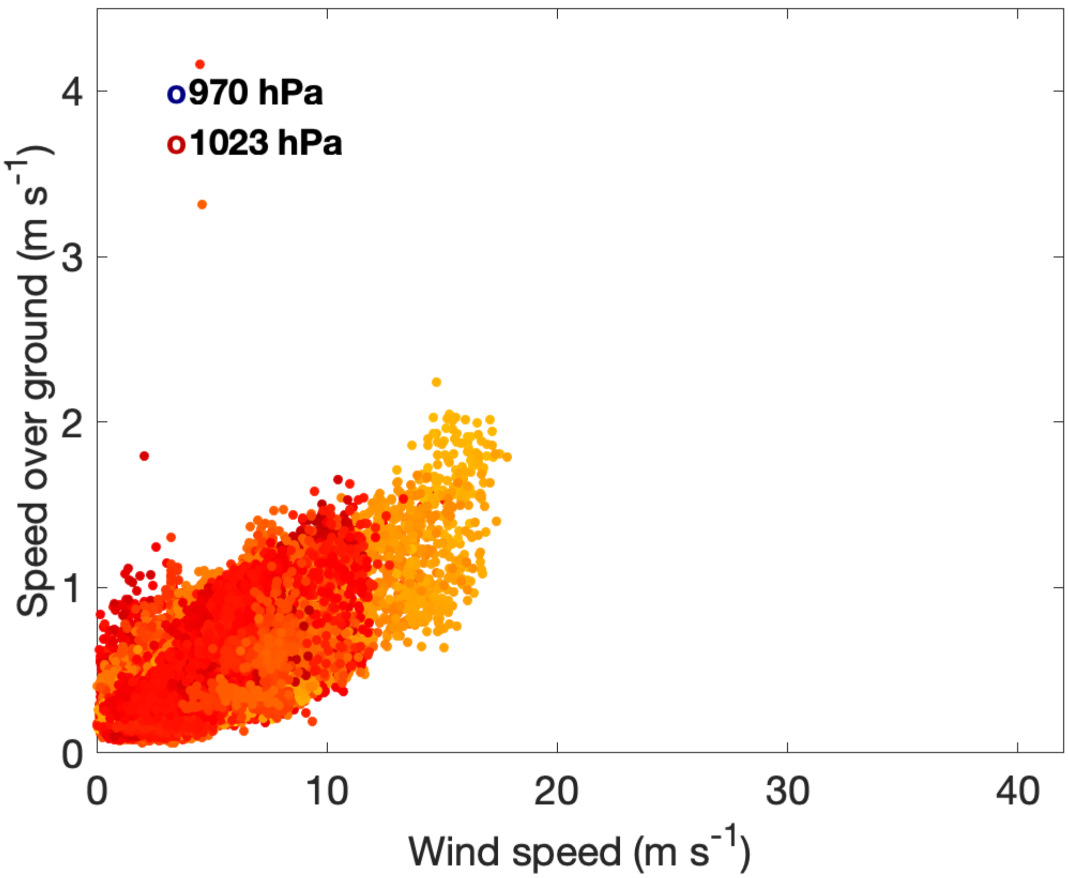

Figure 15 Scatterplot of SD-1032's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

2.6 SD-1059 (Ian)

The primary mission for SD-1059 was to follow a glider between the coast of Georgia and the Gulf Stream (Fig. 2). However, at 15:00 UTC September 23, some of the hurricane forecast models brought Ian eastward across Florida and over then back over the ocean. At the time, SD-1059 was at about 30.4ºN, 80.4ºW. We immediately direct SD-1059 southward in an attempt to intercept Hurricane Ian. Our goal was to wait for the center of Ian to approach SD-1059 and then direct SD-1059 to the east and into the Gulf Stream, which would take SD-1059 rapidly northward, following Hurricane Ian. We succeeded in getting SD-1059 through the center of Ian after it had re-intensified to a hurricane (Fig. 16). However, SD-1059 did not make it to the Gulf Stream in time to follow Ian northward. As SD-1059 approached the Gulf Stream, there is a noticeable increase in SST (Fig. 16). There is a noticeable leveling off of SD-1059's forward speed for wind speeds above 10 m s^{-1} (Fig. 17). This is due to unfavorable currents as we directed SD-1059 toward the Gulf Stream combined with stopping of the vehicle and directing it into the winds as conditions deteriorated (significant wave heights of 8 m and sustained tropical storm-force winds; Fig. 16).

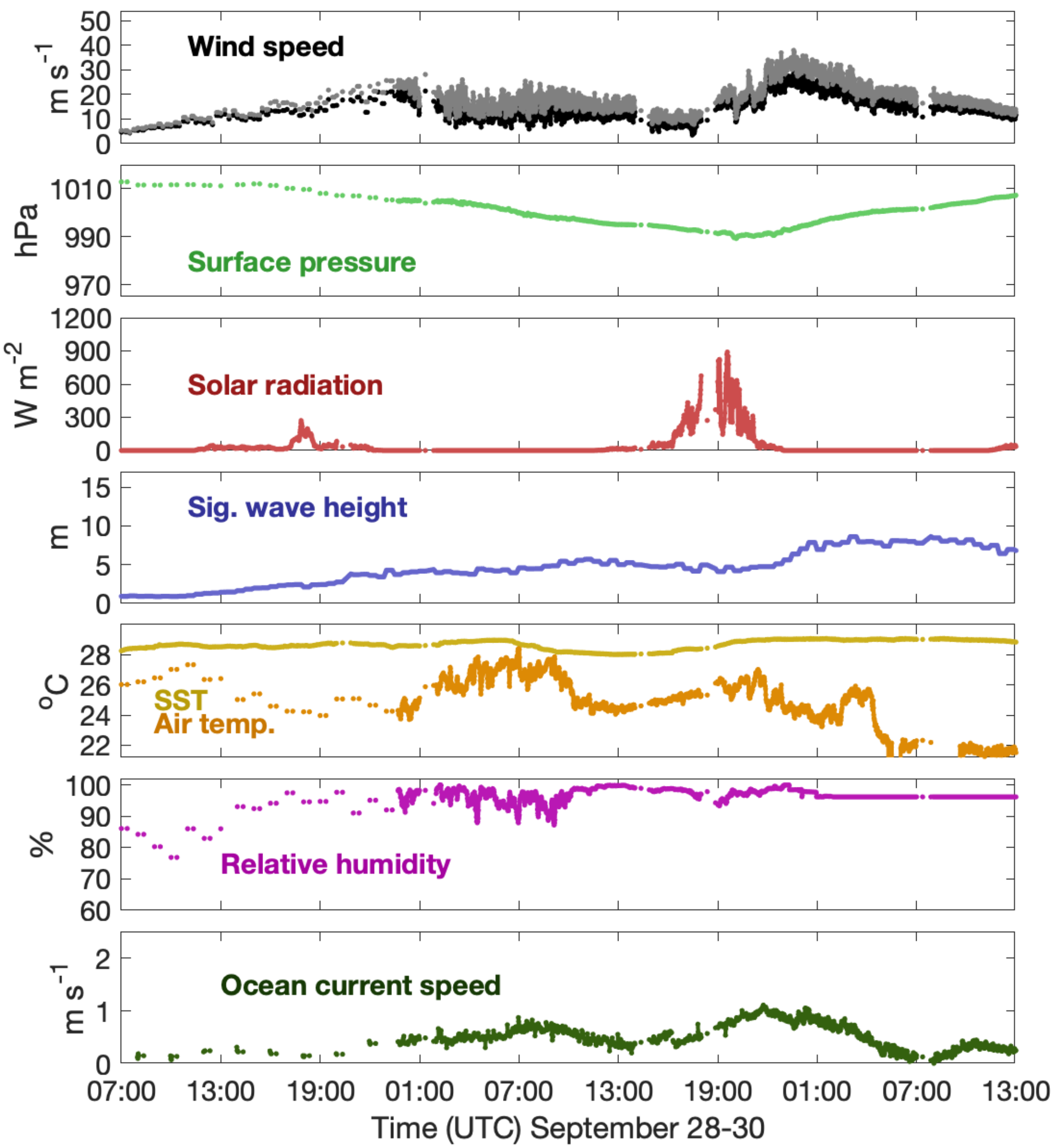

Figure 16 Key measurements (1-minute averages for most variables) from SD-1059 in Hurricane Ian.

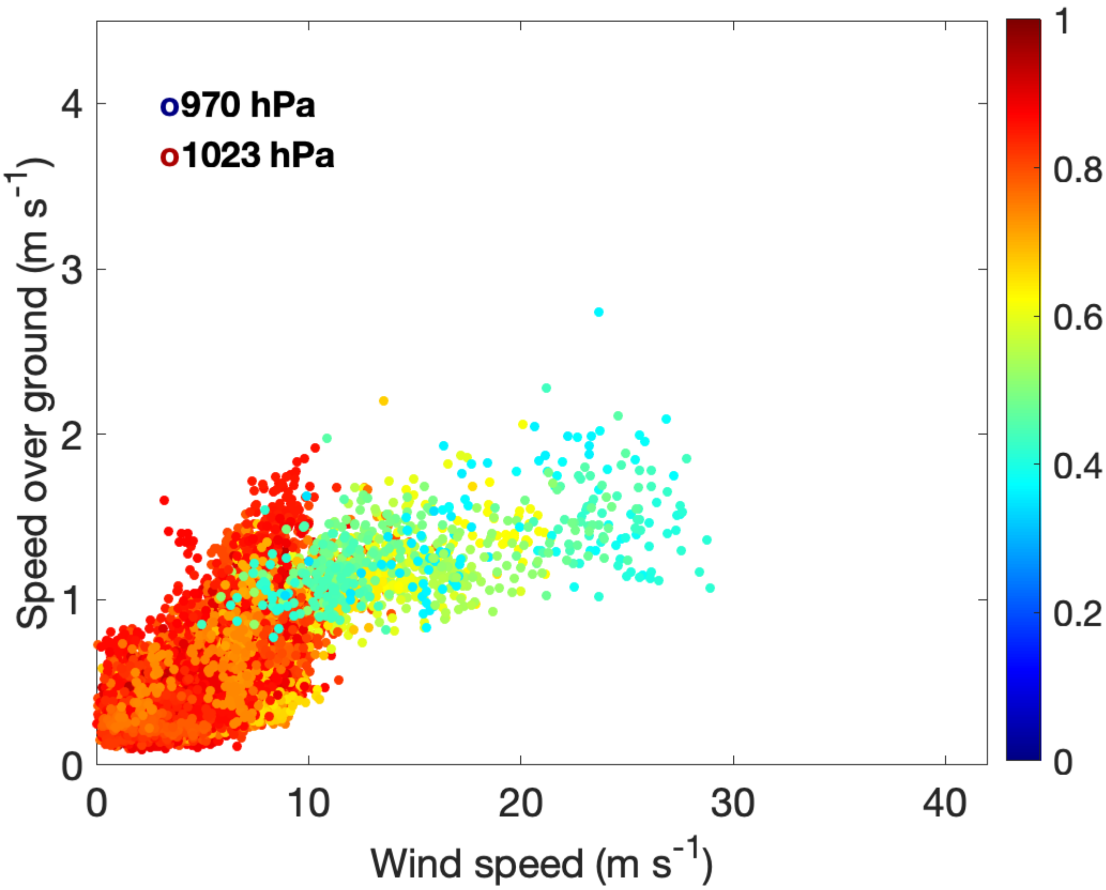

Figure 17 Scatterplot of SD-1059's speed over ground vs. measured 1-min. wind speed for the duration of its mission, color-coded by measured barometric pressure (rainbow palette with extremes shown in legend).

3 Lessons learned

1. Instrument failures created gaps in data collection, sometimes in critical periods.
2. The slow speed of the Explorer saildrones led to large distances from paired underwater gliders and missed opportunities for observations inside hurricanes.
3. Without clearance for operating in some foreign Exclusive Economic Zones (EEZs), vehicle navigation was sometimes complicated and inefficient, and observations had to be halted when vehicles drifted into a foreign EEZ.
4. Marine platforms (e.g., oil rigs) limited the observing capabilities in the western GoM.