ABSTRACT: On 30 September 2021, a saildrone uncrewed surface vehicle (USV) was steered into category 4 Hurricane Sam, the most intense storm of the 2021 Atlantic hurricane season. It measured significant wave heights up to 14 m (maximum wave height = 27 m) and near-surface winds exceeding 55 m s⁻¹. This was the first time in more than seven decades of hurricane observations that in real time a USV transmitted scientific data, images, and videos of the dynamic ocean surface near a hurricane’s eyewall. The saildrone was part of a five-saildrone deployment of the NOAA 2021 Atlantic Hurricane Observations Mission. These saildrones observed the atmospheric and oceanic near-surface conditions of five other tropical storms, of which two became hurricanes. Such observations inside tropical cyclones help to advance the understanding and prediction of hurricanes, with the ultimate goal of saving lives and protecting property. The 2021 deployment pioneered a new practice of coordinating measurements by saildrones, underwater gliders, and airborne dropsondes to make simultaneous and near-collocated observations of the air–sea interface, the ocean immediately below, and the atmosphere immediately above. This experimental deployment opened the door to a new era of using remotely piloted uncrewed systems to observe one of the most extreme phenomena on Earth in a way previously impossible. This article provides an overview of this saildrone hurricane observations mission, describes how the saildrones were coordinated with other observing platforms, presents preliminary scientific results from these observations to demonstrate their potential utility and motivate further data analysis, and offers a vision of future hurricane observations using combined uncrewed platforms.
Tropical cyclones (TCs) can cause severe destruction of property and loss of life in many parts of the world. Coastal areas are affected by strong winds and storm surge, while inland areas are susceptible to flooding from heavy rainfall. Their damage is expected to worsen with climate change, especially sea level rise, and continued coastal development (Elsner et al. 2008; Knutson et al. 2010; Woodruff et al. 2013; Iglesias et al. 2021; Strauss et al. 2021). Mitigating damage and preventing casualties from TCs depend on accurate track and intensity forecasts. Although intensity forecast errors have decreased over the past decade, many challenges remain (Cangialosi et al. 2020). Top research and forecast priorities are the improved understanding and prediction of rapid intensification, defined as an increase in maximum sustained wind speed of at least 15 m s$^{-1}$ over a period of 24 h or less (Kaplan et al. 2010; Gall et al. 2013). Storms undergoing rapid intensification close to land often pose a serious threat because of the limited time for preparation and evacuation.

It has long been recognized that air–sea interaction plays an important role in TC intensity change (Emanuel 1986; Rotunno and Emanuel 1987). The extreme winds, intense rainfall, high ocean surface waves, and copious sea spray in hurricanes push the surface exchanges of energy, water vapor, and momentum into uncharted regimes. Hurricane-induced ocean mixing is another process that is not completely understood and is currently represented in numerical models only via parameterization. Most of the mixing and entrainment of cooler water from below is caused by strong wind-driven vertical shear of horizontal currents (Sanford et al. 2007; D’Asaro et al. 2007). The vertical current shear and ocean circulation under a hurricane are complex and depend on the storm quadrant, intensity, size, and translation speed as well as ocean stratification and wave properties (Price 1981; Price et al. 1994; Sullivan et al. 2012; Chen et al. 2013; Rabe et al. 2015; Reichl et al. 2016; Chen and Curcic 2016; Zhang et al. 2020; Fan et al. 2022).

In situ observations of the sea state and air–sea fluxes in hurricanes are very limited, especially in extreme conditions beneath the eyewall. Direct measurements in the vicinity of the eyewall are key for understanding air–sea fluxes of energy and momentum, which affect storm intensity. However, it is extremely difficult to obtain direct measurements of the upper ocean, air–sea interface, and marine atmospheric boundary layer inside hurricanes because of the harsh environment (e.g., strong winds and ocean currents, large waves,
heavy rain) over remote oceans. Nonetheless, the past decades have witnessed progress in advancing observations of hurricane air–sea interaction on several fronts.

Since the 1950s, data from hurricane reconnaissance aircraft have been extremely valuable for advancing knowledge of ocean–atmosphere processes in hurricanes and improving intensity forecasts (Rogers 2021). GPS–tracked dropsondes and flight-level data have greatly improved our understanding of air–sea fluxes and the dependence of the drag coefficient \( (C_d) \) on wind speed (Powell et al. 2003; Holthuijsen et al. 2012; Bell et al. 2012). However, typically several years’ worth of individual profiles obtained in TCs are needed for statistical robustness (Powell et al. 2003; Holthuijsen et al. 2012). Starting in the 1970s, in situ ocean observations have been made using moorings and drifting buoys, and more recently profiling floats, underwater gliders, and other observing platforms (Domingues et al. 2019). Aircraft-deployed ocean profilers provided information of the upper-ocean responses to TCs (Shay et al. 1992). Moored buoys typically measure near-surface winds, air temperature, humidity, barometric pressure, sea surface temperature and salinity, current, and surface waves. Measurements from moored buoys are commonly considered the gold standard of ocean surface observations, against which other types of surface observations have been compared (Zhang et al. 2019). Surface enthalpy and momentum fluxes can be estimated under TC conditions using data from moored buoys when TCs passed over them (Potter et al. 2017). Autonomous drifting devices (e.g., surface drifters, floats) and remotely steered uncrewed vehicles (e.g., underwater gliders) can measure some of the variables that moored buoys do. Ocean drifters deployed in the Gulf of Mexico in recent years have shown that hurricane-induced surface waves can have a significant impact on upper-ocean currents and mixing through the Stokes effect (Curcic et al. 2016). The TC–ocean current–wave interactions play a significant role in TC intensity forecasts (Kim et al. 2022). Pilot networks of gliders are already in place in the tropical Atlantic, Caribbean Sea, and Gulf of Mexico to monitor the upper hundred meters of ocean features that contribute to TC intensity changes (Miles et al. 2021). Small uncrewed aircraft systems (sUAS) launched during hurricane reconnaissance flights and remotely piloted from the aircraft from a distance of less than \( \sim 25 \) km have been developed and deployed into hurricanes to measure the atmospheric boundary layer (heights of 200–1,500 m) for up to an hour at a time (Cione et al. 2008, 2020). Another milestone in hurricane observations was a Wave Glider USV that was directed into a typhoon in 2013 to measure winds and ocean currents (Mitarai and McWilliams 2016). None of them, however, currently carries the suite of sensors that measures all variables needed for calculations of surface enthalpy fluxes and transmits them to GTS in real time.

The advantage of using different types of observing assets in combination has been demonstrated in intensive field campaigns targeting hurricane air–sea interaction. In the CBLAST program (Black et al. 2007) during the 2003/04 hurricane seasons, multiple aircraft with radars, lidars, and air-deployed GPS dropsondes, ocean drifters, and floats were deployed to observe extreme wind, precipitation, surface waves, ocean currents, and temperature in hurricanes, including upper-ocean mixing using APEX floats in all quadrants of hurricanes (Sanford et al. 2007). Observations combined with laboratory experiments (Donelan et al. 2004) and coupled atmosphere–wave–ocean model simulations (Chen et al. 2007; Lee and Chen 2012) demonstrated that the air–sea fluxes and atmospheric boundary layer and ocean mixed layer are quite asymmetric around a storm with complex features representing various air–sea interaction processes. The deployment of airborne ocean floats, drifters, and dropsondes during the ITOP field campaign in 2010 (D’Asaro et al. 2014) revealed the development of a stable atmospheric boundary layer in the near-storm cold-wake region, which can directly impact the inner-core structure and intensity (Lee and Chen 2014).
These and other observing assets have substantially advanced our ability to measure air–sea interactions in hurricanes, but the need remains for simultaneous measurements of the ocean state and the atmosphere near the sea surface for estimating air–sea fluxes and transmitting observations within hurricanes to operational forecast centers in real time. This gap must be filled to enable direct measurements of the entire air–sea transition zone (upper ocean, air–sea interface, and near-surface atmosphere) to assist hurricane prediction (Miles et al. 2021; Foltz et al. 2022). To help fill that gap, saildrones, a type of USV, have recently been modified to sustain severe weather conditions such as those under hurricanes.

In this article we provide an overview of an experimental Atlantic hurricane observations mission, which took place during August–November 2021 using severe weather saildrones. A unique set of ocean–atmosphere measurements was made throughout the mission, including continuous measurements of near-surface winds, humidity, air and ocean temperature, salinity, wave height and period, and vertical profiles of ocean currents. For the first time, all of these measurements were made continuously by a USV through the eyewall of a major hurricane, and some of the data were transmitted in real time to be available to operational forecast centers. We will also present initial analyses of the data, discuss their potential value for addressing gaps in knowledge of hurricane–ocean interaction and forecast model initialization, and envision the future of observations in hurricanes using combined uncrewed systems. We fully acknowledge that currently there is no single platform that can provide observations to fully represent the entire air–sea transition zone, which, however, may be done using observations from different platforms. We thus coordinated saildrones with underwater gliders and aircraft-released dropsondes to make nearly collocated observations of the upper ocean, air–sea interface, and marine atmospheric boundary layer. This effort of assessing the feasibility and value of combining measurements from different platforms to represent the air–sea transition zone is briefly reported in this article.

Platforms and instruments

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.

Saildrones are the product of a fruitful collaboration between NOAA Research and Saildrone, Inc., through a public–private partnership (Meinig et al. 2019). They have been used to assess the prey field of northern fur seals (Mordy et al. 2017; Kuhn et al. 2020), survey fisheries along the west coast of North America (Chu et al. 2019) and in the U.S. Arctic (Levine et al. 2021), substitute for the NOAA fleet when fishing surveys were canceled due to the COVID-19 pandemic (De Robertis et al. 2021), and validate numerical model prediction (Zhang et al. 2022). Estimates of air–sea fluxes of energy, momentum and carbon dioxide have been made using saildrone observations in the tropics (Zhang et al. 2019), Arctic (Chiodi et al. 2021), and Southern Ocean (Sutton et al. 2021). Saildrones have endured the harshest ocean conditions on the planet, including encountering Arctic sea ice (Chiodi et al. 2021), circumnavigation of Antarctica (Sutton et al. 2021), and inside a category 4 hurricane (Foltz et al. 2022) that will be described in detail in this article. Because of their mobility, saildrones are suitable for adaptive observations of phenomena of particular interest (Gentemann et al. 2020).

The most commonly used saildrone model, Explorer (Zhang et al. 2019), was modified to increase its resilience under extreme weather conditions such as hurricane-force winds. To this end, the wing height was reduced from 5 to 3 m, and the anemometers were mounted at a lower height on top of their wings (Fig. 1). The new design is based on lessons learned from previously damaged wings by heavy waves that broke near the upper midpoint of the 5-m wing. The new wing was tested in a deployment to observe Pacific winter storms.
Five extreme weather saildrones were deployed for the 2021 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 five saildrones were equipped with additional shortwave Delta-T Devices SPN-1 pyranometers and longwave Eppley PIR pyrgeometers. Information of the sensors used in the 2021 deployment is given in Table 1. Details of sensor accuracy are available in Zhang et al. (2019) and Zhang et al. (2022). Results presented in this study are based on observations at the instrument heights. Based on our preliminary analysis, the lowest height of the anemometer in Hurricane Sam was 2.7 m (in comparison with its standard height of 3.4 m).

The near-real-time data stream from saildrone to end users is outlined in Fig. 2. Data are transmitted from the vehicles to Saildrone, Inc., where they are packaged into netCDF Climate and Forecast (CF) files and transferred to the NOAA PMEL online once every 2 h (on the even hours). The netCDF files contain 1-min observations for meteorological and oceanic variables (Table 1) and are self-documented with complete sensor metadata. Once received, the data are made available to mission scientists and collaborators via data delivery services in the formats they choose. PMEL archives the original netCDF data at NCEI and makes the data available through a data server for public access.

For the use by global modeling and operational weather services, data from selected sensors (marked by asterisks in Table 1) are relayed to the NOAA NDBC, where they are converted into the standard WMO BUFR template for surface vehicles (header IORX01 KWNB, BUFR TM315011) and placed on the GTS. This is the current practice since 2019. Prior to that, the 1-min averages were taken at the top of every 10 min without SSS and transmitted to GTS using the surface drifter template.

There is an onboard data acquisition procedure that includes motion corrections of the wind relative to Earth while taking into consideration the pitch, roll, heave, yaw, and...
horizontal motion of the vehicles. Specifically, the three-dimensional wind velocity is measured at 20 Hz in sync with the combined GPS inertial navigation system (INS) and inertial measurement unit (IMU) installed near the ultrasonic anemometer on the saildrone wing that recorded the three-axis motion and speed over ground (SOG) of the sensor. The motion correction follows the recommendation of Edson et al. (1998) and Miller et al. (2008). The resulting motion corrected winds have compared favorably with moored buoy and shipboard measurements (Zhang et al. 2019) and are suitable for direct covariance flux calculations (Reeves Eyre et al. 2023) in the tropical Pacific for low and medium winds. For high wind regimes, it is impossible to find independent in situ high-quality measurements to cross validate the saildrone measurements. Any in situ measurements near the air–sea interface would be useful to validate satellite wind products. For example, Ricciardulli et al. (2022) found excellent agreement between the saildrone and satellite wind measurements during category 4 Hurricane Sam.

The wave parameters are derived from the high-frequency measurements of the VN-300 IMU installed in the saildrone hull, including its 4-Hz heave data, following the methodology developed for the Wave Glider USV with the IMU measurements (Thomson et al. 2017). The significant wave height is calculated as 4 times the square root of the zeroth moment of the wave spectrum over 30-min records, while the peak period is the reciprocal of the frequency

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Variable (1- and 5-min averages available in near–real time)</th>
<th>Manufacturer’s accuracy</th>
<th>Height (above sea surface)</th>
<th>Sampling frequency and default schedule (changeable in real time as needed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anemometer: Gill Windmaster 3D Ultrasonic 20Hz</td>
<td>Wind speed and direction*</td>
<td>±1.5%</td>
<td>3.5 m</td>
<td>20 Hz Always on</td>
</tr>
<tr>
<td>Light sensor: Li-Cor Li-192SA</td>
<td>Photosynthetically active radiation</td>
<td>±5%</td>
<td>2.6 m</td>
<td>1 Hz Always on</td>
</tr>
<tr>
<td>Humidity and temperature probe: Rototronic HC2-52</td>
<td>Air temperature and relative humidity*</td>
<td>±0.8%</td>
<td>2.3 m</td>
<td>1 Hz Always on</td>
</tr>
<tr>
<td>IR Pyrometer: Heitronics CT15.10</td>
<td>Skin sea surface temperature</td>
<td>±(0.5°C + 0.7% target-housing T)</td>
<td>2.3 m</td>
<td>1 Hz Always on</td>
</tr>
<tr>
<td>Dual GNSS-aided VectorNav IMU VN300</td>
<td>Surface wave height and period*</td>
<td>Heave: ±5% or 5 cm</td>
<td>0.3 m</td>
<td>20 Hz Always on</td>
</tr>
<tr>
<td>Barometer: Vaisala BAROCAP PTB210</td>
<td>Surface pressure*</td>
<td>±0.15 hPa</td>
<td>0.2 m</td>
<td>1 Hz Always on</td>
</tr>
<tr>
<td>Sea-Bird SBE 63</td>
<td>Dissolved oxygen</td>
<td>±2% saturation</td>
<td>−1.5 m</td>
<td>1 Hz 12 bursts per 5 min</td>
</tr>
<tr>
<td>CTD:Seabird SBE37</td>
<td>Water temperature and salinity*</td>
<td>T: ±0.0002°C C: ±0.003 mS cm⁻¹</td>
<td>−1.5 m</td>
<td>1 Hz 12 bursts per 5 min</td>
</tr>
<tr>
<td>Fluorometer: Wetlabs ECO FL-S-G4</td>
<td>Chlorophyll</td>
<td>—</td>
<td>−1.8 m</td>
<td>1 Hz 12 bursts per 1 min</td>
</tr>
<tr>
<td>ADCP: Teledyne Workhorse 300 kHz</td>
<td>Ocean current (upper 100 m)</td>
<td>0.5 cm s⁻¹</td>
<td>−1.9 m</td>
<td>1 Hz Always on</td>
</tr>
<tr>
<td>Pyranometer Delta-T SPN1</td>
<td>Downward shortwave radiation</td>
<td>±5%</td>
<td>2.8 m</td>
<td>5 Hz Always on</td>
</tr>
<tr>
<td>Pyrgeometer Eppley PIR</td>
<td>Downward longwave radiation</td>
<td>5 W m⁻²</td>
<td>0.7 m</td>
<td>1 Hz Always on</td>
</tr>
</tbody>
</table>
corresponding to the highest peak in the power spectrum (Earle 1996). Zhang et al. (2023) reported good agreement of significant wave height and wave period between saildrone and NDBC buoy measurements in winter storms of the North Pacific with significant wave height of more than 8 m. During Hurricane Sam, the bulk maximum significant wave height is 14.6 m and the maximum individual wave height based on the 4-Hz heave data is 27 m, consistent with the statistics that the latter should be about twice the former.

Once data are received by PMEL, no automated quality control (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-, 4-, or 1-Hz observations (Table 1). High-resolution data for short periods can be telemetered in near–real time as needed.

Underwater gliders have been used to observe temperature and salinity profiles continuously in targeted ocean features in the Atlantic basin and the Caribbean Sea, where hurricanes intensify and/or weaken, and in locations where other profile observations are not available or feasible, such as coastal regions, and near strong boundary currents (Miles et al. 2021). Data distribution through the GTS in near–real time is typically conducted with a maximum latency of a few minutes ($\lesssim 10$ min) after the data are transmitted at the end of each dive. These observations have led to improved representation of key ocean features in numerical models, which in many cases result in a reduction of hurricane intensity forecast errors within NOAA’s experimental ocean–atmosphere forecast models (Dong et al. 2017). For example, gliders observed the low-salinity barrier layer in the Caribbean region that suppressed mixing, which was crucial to the intensification of Hurricane Maria in 2017 (Domingues et al. 2021). In addition, a combination of glider and Argo float observations were the main
contributors to correctly represent the water mass properties and dynamic features (e.g., Loop Current and associated ring, cyclonic eddy, and low-salinity waters of Mississippi River origin) in an experimental NOAA coupled model that were connected to the intensification of Hurricane Michael in 2018 (Le Hénaff et al. 2021).

GPS dropsondes are atmospheric profiling instruments deployed from aircraft, measuring vertical profiles of the same variables as balloon radiosondes. They are powerful tools for observing the atmosphere under a variety of conditions, including those of hurricanes (Wang et al. 2015). Over the 7–12 min it takes for a dropsonde launched at the flight-level altitude to reach the surface, their radio transmitters send measurements to aircraft twice (temperature, humidity, pressure) or four times (wind speed and direction) per second and then to the GTS. The last data point nearest to the surface is within 5 m of the sea surface. The measurement errors of the dropsondes were reported to be 0.2–5.0 m s\(^{-1}\) for wind, 0.2°C for temperature, <5% for relative humidity, and 1.0 hPa for pressure (Hock and Franklin 1999). More recent dropsondes measure surface wind speed with an accuracy of 1.5 m s\(^{-1}\) (Black et al. 2017).

Mission description
The mission objectives of the 2021 saildrone hurricane observations are as follows:

1) Measure the near-surface atmosphere and sea state to calculate energy and momentum fluxes between the atmosphere and ocean outside and within hurricanes.
2) Synchronize the operations of saildrones and underwater gliders to measure the coupling between the upper ocean and atmosphere.
3) Transmit data in near–real time to operational weather prediction centers to improve atmosphere–ocean initial conditions in forecast models.
4) Apply the observations to understand how air–sea interaction affects hurricane intensity and to advance hurricane prediction models.

Preparations. The top priority of the mission was to obtain measurements inside at least one hurricane to test the feasibility of using the extreme weather saildrones (Fig. 1) as viable tools for hurricane observations. Preseason outlooks had called for the 2021 hurricane season to be more active than normal,\(^3\) but seasonal forecasts do not provide information on where tropical cyclones are more or less likely to travel. Saildrone observation areas were selected based on historical tracks and intensities of tropical cyclones. We first calculated the odds of each 1° × 1° grid box experiencing TS-force winds (>18 m s\(^{-1}\)) during August–October, using 2000–19 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 4-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 (2000–19). 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. 3a).

\(^3\) www.noaa.gov/news-release/noaa-predicts-another-active-atlantic-hurricane-season
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 five saildrones, each at a different location, would experience TS-force winds. We decided on a set of five areas that would give us a 95% chance of at least one saildrone experiencing TS-force winds (boxes in Fig. 3a). It represents a balance between areas north of Puerto Rico and east of the Caribbean that have experienced more major hurricanes (black lines in Fig. 3a) and areas in the subtropics that have less major hurricane hits but larger overall odds of a TC hit (colors in Fig. 3a). The areas are also close to several surface meteorological buoys that would be useful for data comparison purposes (black dots in Fig. 3a).

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. 3a). A series of glider deployments was also planned in the near-coastal region of the southeastern United States during the hurricane season, so one saildrone was deployed in that area (red triangle in Fig. 3a). Finally, because of the saildrones’ shorter wings and slower sailing speeds, we attempted to avoid areas with strong ocean currents (pink contours in Figs. 3a,b), such as the Gulf Stream. 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.

Even with the saildrones deployed in areas of high probabilities of occurrence of TCs, extra steps were needed to maximize the chances for saildrones to penetrate a storm, especially to be close to hurricane eyewalls. Knowing that a saildrone’s motion and position would highly depend on the strong surface winds immediately ahead of a storm, we
estimated saildrone tracks using wind and ocean current data from numerical simulations of a hurricane by a regional atmosphere–ocean coupled model (Warner et al. 2010). Based on our experience from previous saildrone deployments, we used the following formula to calculate the motion of a saildrone:

\[
\begin{align*}
\Delta x &= \left[ \Omega W \cos(\phi) + U \right] dt, \\
\Delta y &= \left[ \Omega W \sin(\phi) + V \right] dt,
\end{align*}
\]

where \( \Delta x \) and \( \Delta y \) are saildrone displacement in zonal and meridional directions, respectively, \( \Omega = 0.115 \) is the wind efficiency to move a saildrone (based on past deployment statistics), \( \phi \) an angle of the intended motion direction to the predicted storm center (zero toward the east and increasing counterclockwise), \( U \) and \( V \) the modeled current velocities, \( W \) the modeled surface wind speed, and \( dt \) is 15 min. The wind-driven saildrone speed is capped to a maximum of 3.3 m s\(^{-1}\) (the vessel’s hull speed). A large number of such calculations were made along the simulated hurricane track to include different wind and oceanic current conditions. In the example given in Fig. 4, 6 h ahead of a hurricane, a saildrone would have higher chances to reach the eyewall if positioned to the right of the predicted hurricane track. The same exercise was conducted using operational forecast products during the mission and led to an operation guideline that helped us to steer a saildrone to the eyewall of category 4 Hurricane Sam in 2021.

**Deployment.** The deployment information is given in Table 2. Two saildrones were launched from Jacksonville, Florida, on 23 July 2021, and transited to observing areas D and E (Figs. 3 and 5). Three saildrones for observing areas A, B, and C were launched from

<table>
<thead>
<tr>
<th>ID</th>
<th>Launch and recover dates</th>
<th>Data period</th>
<th>Main observation area</th>
<th>Time paired with gliders (&lt;10 km)</th>
<th>Comparison time with buoys (&lt;14 km)</th>
<th>Number of dropsondes nearby (&lt;200 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1031</td>
<td>23 Jul, 1 Dec</td>
<td>1 Aug–6 Nov</td>
<td>D, E</td>
<td>0 days</td>
<td>6 h</td>
<td>5</td>
</tr>
<tr>
<td>1040</td>
<td>23 Jul, 1 Dec</td>
<td>1 Aug–6 Nov</td>
<td>E</td>
<td>19 days</td>
<td>41 h</td>
<td>0</td>
</tr>
<tr>
<td>1045</td>
<td>29 Jul, 25 Nov</td>
<td>1 Aug–27 Oct</td>
<td>A'</td>
<td>0 days</td>
<td>0 h</td>
<td>1</td>
</tr>
<tr>
<td>1048</td>
<td>29 Jul, 29 Nov</td>
<td>1 Aug–16 Nov</td>
<td>B</td>
<td>53 days</td>
<td>31 h</td>
<td>16</td>
</tr>
<tr>
<td>1060</td>
<td>29 Jul, 29 Nov</td>
<td>1 Aug–16 Nov</td>
<td>C</td>
<td>51 days</td>
<td>0 h</td>
<td>7</td>
</tr>
</tbody>
</table>
Saint Thomas, U.S. Virgin Islands, on 29 July. The saildrone tasked to observing area A was modified to sample a different area A' because strong westward currents and winds substantially slowed its eastward motion. Real-time data transmission to the GTS started on 1 August and ended on different dates for different saildrones. A total of 502 days of saildrone observations were made during the mission.

One objective of the NOAA saildrone deployments has been proper cross validation, both in terms of intraplatform validation (among saildrones) and interplatform (between saildrones and other platforms) comparison (Cokelet et al. 2015; Zhang et al. 2019). During the 2021 hurricane observations mission, three saildrones were brought together and sailed side by side for 2 days immediately after launch and again before retrieval at Saint Thomas, so their measurements could be directly compared. The two saildrones launched from Jacksonville underwent the same cross validation. A summary of interplatform cross validation with gliders, buoys, and dropsondes is given in Table 2. Four of the saildrones were coordinated with underwater gliders for a total of 123 days to make near-collocated measurements of surface meteorological, near-surface ocean, and subsurface ocean data. Three of the saildrones sampled near moored buoys (dots in Fig. 5) for a total of 78 h to compare their similar surface observations. Finally, 29 dropsondes were launched near saildrone locations (within 200 km) from eight aircraft flights (NOAA P-3 and NASA DC-8). These coordinated measurements...
provided opportunities not only to cross validate their data, but also to practice observing the air–sea transition zone using different types of uncrewed observing systems.

During the 2021 mission, the saildrones observed one category 4 hurricane (Sam) and five other TCs: Grace (category 3), Fred (category 1), Henri (category 1), Mindy (TS), and Peter (TS) (Fig. 5). The saildrones observed Grace and Henri when they were TSs, before they became hurricanes. The maximum wind speeds of these tropical cyclones observed by the saildrones and the estimated shortest distances between the vehicles and the storm tracks are listed in Table 3. This success resulted from a combination of careful decisions on the targeted observation areas and positioning of the saildrones ahead of the storms (see “Preparations” section).

Preliminary scientific results

Full analysis of the saildrone data from the 2021 hurricane observations mission is underway. Here, we present preliminary results to demonstrate the utility of the data and to motivate additional studies. We first compare observations from saildrones with those from other platforms (moored buoys, airborne dropsondes, and underwater gliders), followed by comparisons between observations and numerical model outputs. We then use observations to address an intriguing scientific issue.

Three saildrones and NDBC buoy\(^4\) comparison periods were available with separation distances of less than 14 km, for 78 h total (SD-1031 versus NDBC 41002, 0500–1100 UTC 28 August 2021; SD-1040 versus NDBC 41008, 0600 UTC 15–2400 UTC 16 August 2021; and SD-1048 versus NDBC 42059, 1400 UTC 5–1800 UTC 6 August 2021). Figure 6 shows an example of the comparison of temperature and wind between a saildrone and a buoy at 15.25°N, 67.48°W over 31 h with a separation of 4–6 km. The 1-min real-time saildrone measurements were averaged over 10-min intervals to match the 10-min NDBC measurements, some of which were missing. The vertical separation between equivalent instruments on the two platforms was less than 1.6 m in the air (3.5 m on saildrones versus 5 m on NDBC buoys) and negligible in the water. No scaling to standard heights has been applied here. During the comparison the mean differences between the measurements from the two platforms are \(0.070°C, 0.10 \text{ m s}^{-1}, 5.4°, 0.04 \text{ m}, \text{ and } 0.06 \text{ s for air temperature, wind speed and direction, significant wave height, and peak wave period, respectively. The average and standard deviation of the differences during the three comparisons for all common variables are given in Table 4. There are significant discrepancies (beyond 95% confidence intervals) in the atmospheric pressure and relative humidity measurements.}

Twenty-nine dropsondes were launched near four saildrones (within a 200 km radius) to assess the degree to which dropsondes can provide profiles of the atmospheric

<table>
<thead>
<tr>
<th>Tropical cyclone</th>
<th>Best track TC lifetime maximum wind and minimum pressure</th>
<th>Shortest distance between saildrones and TC tracks</th>
<th>Time at the shortest distance</th>
<th>Best track max wind and min pressure at shortest distance</th>
<th>Saildrone observed max wind (gust), min pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fred</td>
<td>28.3 m s(^{-1}), 993 hPa</td>
<td>142 km</td>
<td>0905 UTC 11 Aug</td>
<td>18.1 m s(^{-1}), 1,007 hPa</td>
<td>13.4 (15.7) m s(^{-1}), 1,011 hPa</td>
</tr>
<tr>
<td>Grace</td>
<td>56.6 m s(^{-1}), 962 hPa</td>
<td>38 km</td>
<td>1630 UTC 15 Aug</td>
<td>15.4 m s(^{-1}), 1,011 hPa</td>
<td>13.5 (17.1) m s(^{-1}), 1,011 hPa</td>
</tr>
<tr>
<td>Henri</td>
<td>33.4 m s(^{-1}), 986 hPa</td>
<td>40 km</td>
<td>2355 UTC 20 Aug</td>
<td>30.9 m s(^{-1}), 994 hPa</td>
<td>15.7 (19.6) m s(^{-1}), 1,002 hPa</td>
</tr>
<tr>
<td>Mindy</td>
<td>20.6 m s(^{-1}), 1,004 hPa</td>
<td>54 km</td>
<td>1550 UTC 9 Sep</td>
<td>15.4 m s(^{-1}), 1,005 hPa</td>
<td>15.4 (18.1) m s(^{-1}), 1,007 hPa</td>
</tr>
<tr>
<td>Peter</td>
<td>23.1 m s(^{-1}), 1,005 hPa</td>
<td>328 km</td>
<td>0230 UTC 21 Sep</td>
<td>23.1 m s(^{-1}), 1,007 hPa</td>
<td>16.9 (20.0) m s(^{-1}), 1,014 hPa</td>
</tr>
<tr>
<td>Sam</td>
<td>69.4 m s(^{-1}), 929 hPa</td>
<td>32 km</td>
<td>1605 UTC 30 Sep</td>
<td>64.3 m s(^{-1}), 940 hPa</td>
<td>40.5 (56.5) m s(^{-1}), 970 hPa</td>
</tr>
</tbody>
</table>

\(^4\) NDBC buoy data quality control is documented at www.ndbc.noaa.gov/qc.shtml.
Fig. 6. A comparison of air and water temperatures and wind speed and direction measured by saildrone SD-1048 and NDBC buoy 42059 at 15.25°N, 67.48°W for over 31 h with a separation of 4–6 km. (left) The instrument time series. (right) The difference (saildrone minus buoy) time series (red solid lines with black dots), the mean difference (thick black dashed lines), plus and minus the standard error of the mean (thin dashed black lines), and ±1.96 times the standard deviation of the difference (dashed red lines)—equivalent to the 95% confidence intervals for a Gaussian distribution.
boundary layer above saildrones (Table S2). The first step of this assessment is to compare their near-surface measurements and assess the extent to which their measurements match. Temperature and relative humidity measured by the saildrones and the dropsondes (the last data points before splash) match reasonably well (Fig. 7, top panels), with their biases (mean differences) comparable to or smaller than those between saildrones and buoys (Table 4). Meanwhile, measurements of wind speed and direction from the saildrones and dropsondes differ substantially (Fig. 7, bottom panels), with their biases greater than those between saildrones and buoys (Table 4).

To put this comparison in the context of general uncertainties of dropsondes, we found dropsondes launched by NOAA in the period of 1996–2021 that matched moored buoy observations (within 200 km of their splashing locations). There are 7,685, 4,376, 5,028, and 4,871 matches for temperature, relative humidity, wind speed, and wind direction, respectively. We estimated RMSEs of the dropsondes as their differences from buoy observations. The large RMSEs (gray whiskers in Fig. 7) come from small numbers of samples (outliers): 7%, 3%, 10%, and 12% of the total samples for temperature, relative humidity, wind speed, and wind direction, respectively. If these outliers are removed using an interquartile-range-based outlier

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**Table 4. Saildrone minus NDBC buoy mean differences and standard deviations for three comparisons ≤ 14 km apart over 78 h.**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean</th>
<th>Std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barometric pressure (hPa)</td>
<td>1.01</td>
<td>0.07</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>0.00</td>
<td>0.09</td>
</tr>
<tr>
<td>Water temperature (°C)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>−5.13</td>
<td>1.27</td>
</tr>
<tr>
<td>Wind speed (m s⁻¹)</td>
<td>0.01</td>
<td>0.54</td>
</tr>
<tr>
<td>Wind direction (°)</td>
<td>0.78</td>
<td>7.14</td>
</tr>
<tr>
<td>Significant wave height (m)</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Dominant wave period (s)</td>
<td>0.06</td>
<td>0.68</td>
</tr>
</tbody>
</table>

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**Fig. 7.** Scatter diagrams for surface (a) air temperature, (b) relative humidity, (c) wind speed, and (d) wind direction measured by saildrones and airborne dropsondes within 200 km from saildrones. Distance between saildrones and dropsondes splash locations are marked by colors. Vertical whiskers indicate RMSEs of dropsondes launched during 1996–2021 as their differences from moored buoy observations within 200 km of the splashing locations using all samples (gray) and without outliers (red) (see text for details). Solid lines are best linear fits.
detection method (Barbato et al. 2011), the RMSEs are substantially reduced (red whiskers). In any case, with or without the outliers, the discrepancies between saildrone observations and dropsondes surface data are comparable to the RMSEs of dropsondes. This result calls for further in-depth assessment of the uncertainties of dropsonde data and the feasibility of using them to provide vertical structure of the atmospheric boundary layer above saildrones (e.g., a threshold of distance between the two and possible dependence on environmental conditions).

The coordinated observations by saildrones and underwater gliders allow explorations of how the structural variability at the surface is connected to that in the upper ocean. An example is given in Fig. 8, which shows a time series of surface variables observed by a saildrone and the upper-ocean profiles measured by a nearby glider over a period of 24 days (10–23 August). Their locations are shown in Fig. 8a. There are unmistakable signals of the diurnal cycle in SST (Fig. 8d). Diurnal signals can also be seen in water temperature (Fig. 8g) and salinity (Fig. 8h) in the upper 30 m during certain days. Notice that there is no diurnal signal in surface wind speed (Fig. 8b) or surface salinity (Fig. 8e) measured by the saildrone. This suggests that the diurnal cycle in water temperature is due to daytime solar heating, nighttime longwave cooling, and penetrative convection and mixing. The same mixing process might have helped to produce the diurnal signal in salinity because of the background stratification. There are weak diurnal signals in surface air temperature measured by the saildrone (Fig. 8c), suggesting diurnal influences of the ocean on the atmosphere. Another interesting feature is the freshening in the upper 30 m around 14–18 and 21 August without any freshening signal at the surface. This suggests that the freshening of the upper ocean was caused by advection of lower-salinity water, possibly from the runoff of the Orinoco River (Field 2007; Hernandez et al. 2016). The diurnal air–sea interaction and upper-ocean salinity fluctuations are interesting topics that need further investigation.

Fig. 8. (a) Tracks of a saildrone (red) and a glider (purple), time series of (b) wind speed, (c) air temperature, (d) sea surface temperature (SST), (e) sea surface salinity (SSS) measured by the saildrone, (f) differences between saildrone and glider measured SST (green) and SSS (red) and horizontal distance between the saildrone and glider (blue), profiles of (g) water temperature and (h) salinity measured by the glider. The time period covers 10–23 Aug 2021.
Observations from the paired glider–saildrone deployments north and south of Puerto Rico (Fig. 9a) were used to further assess the performance of the two platforms. During the paired deployments, observed SST and SSS agreed well when the glider and saildrone were in close proximity. The mean absolute difference was less than 0.05°C for SST, and less than 0.1 PSS-78 for SSS, when the two vehicles were located within 6 km of each other (Figs. 9b,c). The bias for the glider versus saildrone was minimal, −0.01°C for SST and 0.01 PSS-78 for SSS, when the vehicles were less than 10 km apart (Figs. 9d,e). SST (SSS) was observed to range from 28.4° to 30.8°C (32.3 to 36.5 PSS-78) and had a standard deviation of 0.5°C (0.7 PSS-78) during these comparisons. Thus, when in close proximity (distance < 10 km), the two platforms provided effectively collocated observations of the upper ocean and air–sea interface. This comparison also highlights that the saildrone measurements of SST and SSS at −1.5 m are representative of the near-surface temperature and salinity, given the good agreement with the glider measurements which were taken to be the average over the top 4 m. Hence, we can use the saildrone observations to fill gaps in the glider observations near the surface.

The observations from the same paired glider–saildrone deployments south of Puerto Rico were used to assess the performance of the NCEP global Real-Time Ocean Forecast System (RTOFS) (Garraffo et al. 2020), which provided initial ocean conditions for the operational coupled hurricane models of NCEP in 2021. When subsampled along the saildrone tracks,
the output from RTOFS shows a clear bias, with colder (−0.1°C) and saltier (+0.35 PSS-78) surface waters (Figs. 9d,e). The bias in salinity is even larger (+0.4 PSS-78) south of Puerto Rico where the surface waters are generally fresher, indicating a reduced SSS gradient across Puerto Rico in the model (Fig. 9a). The observed RTOFS surface bias exceeds the glider–saildrone RMSE by a factor of 1.7 for SST and 3.2 for SSS (Figs. 9d,e). The saildrone and glider SSS agreement is thus well within the model bias, and the combination of these paired measurements, including upper-ocean currents, provide a basis for future work to better understand the reasons for model biases seen here and further improve model performance.

Another example of discrepancies between the model and observations is the diurnal cycle in temperature. Examination of the average diurnal cycle in temperature for the period August–October 2021 shows that not only does RTOFS tend to be colder at the surface, the cold bias is stronger during the daylight hours when the surface waters are at their warmest (Figs. 10a,b). This cold bias persists over the near-surface layer and is of the same magnitude for the temperature averaged over the top 10 m between RTOFS and the glider (Fig. 10c). The vertical sections showing the mean diurnal cycle reveal further differences between model and observations, with a delayed daily maximum at depth and deeper mixed layer depth (MLD) in RTOFS (Figs. 10a,b).

Fig. 10. Vertical sections of the mean diurnal cycle in temperature from (a) glider SG668 south of Puerto Rico and (b) RTOFS sampled as the glider. The mean diurnal cycle is computed as the hourly average of the anomaly from the daily mean, then averaged for the period August–October 2021. White stars mark the time of minimum and maximum temperature anomaly by depth. The cyan line shows the mean diurnal cycle of the mixed layer depth (MLD; the depth at which the potential density has increased compared to the surface by a threshold equivalent to 0.3°C decrease in temperature at constant salinity). (c) Mean diurnal cycles of surface temperature from the glider (at 1 m and top 10 m), from RTOFS sampled as the glider (SST and top 10 m), and from the saildrone (1.5 m).
Turbulent surface heat fluxes released from the ocean to the atmosphere are key for sustaining and strengthening hurricanes. The saildrone-measured enthalpy flux [the sum of latent and sensible heat flux estimated using the COARE 3.0 algorithm of Fairall et al. (2003)] changed dramatically from about 120 W m⁻² before Hurricane Sam to more than 1,100 W m⁻² during Sam. A similar increase in surface enthalpy flux was observed previously for Typhoon Megi (Lin et al. 2013). The enthalpy flux in the Hurricane Weather Research and Forecasting (HWRF) Model prediction sampled along the saildrone track showed a much larger flux both before the hurricane on 29 September and during Sam (Fig. 11). The location of the hurricane eye and the storm’s size produced by the model may have contributed to these differences. The minor peak of solar radiation and slight drop of enthalpy flux at 1600 UTC 30 September in observations suggest that the saildrone was mostly in the eyewall and was at one time close to the edge of the eye, while the larger delayed peak of solar radiation and the corresponding double peaks of enthalpy flux in HWRF suggest that the saildrone track in the prediction was closer to the center of the eye than in observations. It should be pointed out that the enthalpy fluxes within TCs must be treated as crude estimates using bulk flux algorithms given the uncertainties of their parameters under TC-strength wind conditions.

The passage of TS Henri over one saildrone (SD-1031) and Hurricane Sam over another (SD-1045) provided opportunities to assess the ocean’s response to moderate and extreme wind conditions. Henri was a strong tropical storm (30 m s⁻¹ maximum sustained winds) when it passed within 40 km of SD-1031 (Fig. 5, Table 2). However, the saildrone measured maximum 1-min averaged winds of about 15 m s⁻¹ because it was on the weak (left) side of the storm (Fig. 12a). In contrast, SD-1045 recorded winds exceeding 40 m s⁻¹ when it was located 32 km east of Hurricane Sam’s center (Figs. 5 and 12b, Table 2). Despite much stronger winds measured by SD-1045 in Sam, the SST cooling was less than that observed by SD-1031 in Henri (red curves in Figs. 12a,b). In Henri, SST decreased until about 1200 UTC 20 August, when solar radiation increased and warmed the near-surface ocean (red curve in Fig. 12c). Cooling resumed about 12 h later, and the total SST decrease over 48 h was 1.8°C. Ahead of Hurricane Sam, SST increased slightly on 29 September under the influence of solar heating (Figs. 12b,d). SST then increased again during 0800–1400 UTC 30 September despite near-zero solar radiation and increasing cooling from the enthalpy heat flux (Fig. 11). As a result, the total SST decrease in 48 h in Sam was only 0.9°C. Each rise in SST during Henri and Sam (positive values of black curves in Figs. 12c,d) was associated with an increase in surface salinity, with a maximum increase of about 0.7 PSS-78 in Sam as wind speed rapidly increased from 20 to 35 m s⁻¹ and SST increased by 0.2°C.

The difference in total SST cooling between Henri (1.8°C) and Sam (0.9°C) was likely caused by differences in subsurface ocean temperature and salinity (Figs. 12e–h). Ahead of Henri, temperature decreased 2.3°–3.8°C with depth between the surface and 40 m and salinity increased 0.3–0.5 PSS-78. In contrast, ahead of Sam, an inversion caused temperature to

![Fig. 11. Downward solar radiation and air–sea surface enthalpy flux measured by the saildrone and produced by HWRF before, during, and after Hurricane Sam.](image-url)
increase 0.25°–0.35°C over the same depth range, and salinity at 40 m was 0.4–1.5 PSS-78 higher than at the surface. The much stronger temperature stratification and weaker salinity stratification ahead of Henri contributed to larger SST cooling by the storm despite much weaker winds. Under Sam, strong salinity stratification in the upper 40 m led to a barrier layer and supported a temperature inversion, which may have led to an increase in SST as the northern eyewall passed over the saildrone and warmer water was mixed up to the surface. Barrier layers have been previously observed to suppress sea surface cooling by hurricanes (Wang et al. 2011; Balaguru et al. 2012; Domingues et al. 2015). The dominance of vertical mixing in generating the SST changes is supported by the small contributions of the surface enthalpy flux (cf. black and colored curves in Figs. 12c,d) and a much larger increase in surface salinity under Sam (1.5 PSS-78 in 48 h) compared to Henri (0.2 PSS-78 in 48 h), consistent with the differences in prestorm salinity stratification. Future work will further evaluate the roles that upper-ocean thermohaline structure and vertical mixing played in producing the SST changes observed in Hurricane Sam, and the extent to which the observed SST variability was accurately reproduced in operational coupled hurricane model systems.
Concluding remarks and vision for the future

Saildrones modified specifically for severe weather conditions were deployed during the 2021 Atlantic hurricane season in an experimental mission to test the feasibility of using remotely piloted USVs to observe hurricanes. This was the first time that USVs were deliberately steered toward tropical cyclones and provided digital observational data inside and near tropical cyclones to operational forecast centers in real time and photo images and videos of the sea state for public viewing in near–real time.\(^5\)

The most significant achievement of the 2021 saildrone mission of observing hurricanes was the demonstration of the feasibility of using USVs to make measurements near the centers of major hurricanes through careful planning and piloting. This paves the way for deployments of saildrones together with other types of uncrewed systems as an integrated component of the hurricane observing network (Domingues et al. 2019) to benefit prediction. While there are a variety of assets that have been used to observe hurricanes, USVs are the only currently available mobile platforms that are capable of making in situ and targeted measurements of all variables needed to estimate air–sea energy and momentum fluxes in a continuous way, as opposed to snapshots provided by airborne dropsondes. Compared to moored buoys, their mobility affords them higher chances to measure within the eyewalls and in the eyes of hurricanes.

The second most significant achievement of the 2021 saildrone mission during the Atlantic hurricane season was the development of a concept of operations to coordinate different types of observing systems to measure the air–sea transition zone. In our case, the coordination was made between the saildrones and underwater gliders and between saildrones and airborne dropsondes. Our efforts of coordinated observations of the air–sea transition zone can be extended by including other robotic/uncrewed/autonomous devices with complementary conventional observing assets. Flying UAVs above saildrone–glider pairs would add measurements of vertical profiles of the marine atmospheric boundary layer. Over the open ocean, this is currently feasible with two types of UAVs: shipborne, which are not suitable for hurricane observations, and airborne sUAVs, which are designed

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\(^5\) [www.youtube.com/watch?v=Tzgd5Sb0T98](www.youtube.com/watch?v=Tzgd5Sb0T98)
for hurricane observations. While such airborne sUAVs have been developed and tested, they have yet to be deployed in coordination with ocean surface-based observing assets. In future hurricane seasons we plan to experiment with three-way coordinated observations using underwater gliders, saildrones, and sUAVs, supplemented by airborne devices (e.g., aircraft-launched dropsondes, profiling floats, and drifters) to explore the feasibility of collocated and simultaneous measurements of the entire air–sea transition zone both inside hurricanes and in their ambient environment (Fig. 13). Such experimental observations of hurricanes using combined uncrewed systems can also be acquired in other targeted field observations and possibly in future sustained observations over the global ocean.

The measurements made during the 2021 hurricane saildrone mission, though unprecedented and of high quality, are still sparse in their spatial and temporal coverage. Because of this, novel approaches beyond conventional data-denial simulations may be needed to demonstrate the value of saildrone observations to hurricane prediction. Nonetheless, preliminary but promising scientific results obtained so far from the saildrone data demonstrate that new information and knowledge can be harnessed from saildrone measurements that are otherwise not available. Continuing and expanding saildrone observations of hurricanes in coordination with other uncrewed observing systems and conventional platforms will lead to a new observing network that includes long-term sustained, seasonally sampled, and targeted observations to cover the background state, environment, and internal processes as hurricanes form, intensify, and threaten landfall. New observations taken by innovative approaches are needed for improving prediction of hurricanes, especially their rapid intensification. Saildrone is such an innovative approach, with its potential only just beginning to be explored.

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Data availability statement. The data used in this study are available from the following sources:

The saildrone data: https://data.pmel.noaa.gov/pmel/erddap/search/advanced.html?page=1&itemsPerPage=1000&searchFor=saildrone&protocol=%28ANY%29&cdm_data_type=%28ANY%29&institution=%28ANY%29&ioos_category=%28ANY%29&keywords=%28ANY%29&long_name=%28ANY%29&standard_name=%28ANY%29&variableName=%28ANY%29&maxLat=&minLat=&maxLon=&minLon=&maxTime=&minTime=

The underwater glider data: www.ncei.noaa.gov/access/data/global-ocean-currents-database/ioos_glider.html
The airborne dropsonde data: www.aoml.noaa.gov/hrd/data_sub/hurr.html and https://drive.google.com/drivefolders/1K26j3HcdMUrHVzpxQw8Zcr0OnpUL_V7
Best track data: www.nhc.noaa.gov/data/
The NDBC buoy data: www.ndbc.noaa.gov/obs.shtml
The Argo data: https://argo.ucsd.edu/data/
The HWRF data: www.nco.ncep.noaa.gov/pmb/products/hur/
The RTOFS data: https://polar.ncep.noaa.gov/global/data_access.shtml


