

ARTICLE

The Mini Adaptive Sampling Experiment: Simultaneous Deployment of Multiple Ocean Observing Platforms in the Yucatan Channel

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Introduction

The dynamic Loop Current (LC), its northward extension deep into the Gulf, and the formation, reattachment, and eventual separation of LC Eddies (LCEs) that then propagate westward are governed by uncertain physical processes that limit predictability, hamper safe offshore operations, limit the accuracy of hurricane intensity forecasts, and degrade society's ability to manage an economically vital international ecosystem technology (DiMarco et al., 2005; Furey et al., 2018; Jochens & DiMarco, 2008; Nowlin et al., 2001). A safer, and more productive, Gulf depends on risk reduction informed by improved operational forecasts of the region's dominant ocean feature, i.e., the LC/LCE system. This requires coordinated, synergistic, and adaptive observation/modeling campaigns that expand process understanding, improve the forecasts and derive products used for decision-making, and ultimately inform the design of efficient sustained observing systems that remain in place to maintain the forecast skill levels required by stakeholders.

The LC transports about 27 million cubic meters per second of water into the Gulf of America through the Yucatan Channel between Mexico and Cuba (Candela et al., 2019). Despite decades of effort in the public and private sectors, accurate and timely prediction of arrival time, location, and intensity of the current and its associated eddies into the Northern Gulf of America has remained elusive. Unlike traditional hydrographic methodologies that provide geostrophic velocity estimates, ocean buoyancy gliders and subsurface floats that are equipped with direct velocity observations pro-

ABSTRACT

We report the preliminary results of the international MASTR (Mini-Adaptive Sampling Test-Run) Experiment under the UGOS (Understanding the Gulf Ocean Systems) Program. The experiment utilized cutting-edge ocean observing technologies, including autonomous platforms, moorings, aircraft, and high-frequency radar, to collect near-real-time temperature, salinity, and velocity observations in the southeastern Gulf of America and Yucatan Channel. These observations provided critical insights into the complex dynamics of the Loop Current (LC) and its associated eddies, which influence regional circulation and operational predictability. Six ocean buoyancy gliders were deployed in the western Yucatan Strait near Mahahual, México. Four gliders were deployed from January to April 2024; and two, from July to November 2023. The high-frequency radar system near Cancun, México, operational throughout the experiment, observed surface velocity patterns and extreme weather events, including Hurricane Idalia (August 26 to September 2). Radar data captured the spatial and temporal position of the Yucatan Current speed core and revealed the LC system's evolution from a retracted state. Observations exposed the complexity of the LC system, influenced by topographic, tidal, geostrophic, ageostrophic, and wind forcing. Nearly 3,900 temperature and salinity profiles were collected, significantly improving LC and hurricane intensity forecasts. Integrating near-real-time observations into federal and industry models enhanced forecast accuracy. This experiment underscores the value of adaptive sampling in advancing regional circulation understanding and operational forecasting. Findings will inform the 2025 Grand Adaptive Sampling Experiment, support cost-effective observing systems, and improve offshore risk management and hurricane predictions.

Keywords: Yucatan Channel, ocean observing systems, buoyancy gliders, high-frequency radar, drifters

vide the capability to estimate total kinematic variability.

The National Academies of Sciences, Engineering, and Medicine (NASEM) has funded a 5-year international private-public partnership (NASEM Report, 2018) of academic and industry organizations as well as federal agencies led by Texas A&M University, Florida State University, and the Woods Hole Oceanographic Institution and partnered with several U.S. federal government agencies (including National Oceanic and Atmospheric Administration [NOAA], Naval Research Laboratory [NRL], Bureau of Ocean Energy Management [BOEM], and Bureau of Safety and Environmental Enforcement [BSEE]). The primary focus of this re-

search is to improve skill of sustained continuous operational forecasts (Morey et al., 2020) for the reduction of risks in offshore energy exploration and production and to design and implement cost-effective ocean observations, data-assimilation techniques, and improvements to forecast capabilities. The secondary focus is to develop robust linkages with end users and other stakeholders and contribute to improving the accuracy of hurricane (and other ocean hazards) forecasts.

We report on the adaptive sampling element of UGOS (Understanding the Gulf Ocean Systems) called MASTR (Mini-Adaptive Sampling Test Run) to simultaneously deploy multiple autonomous measurement platforms

(i.e., ocean buoyancy gliders, subsurface floats, drogued drifters) and high-frequency coastal radar to provide near-real-time surface and subsurface observations of the deep water southeastern Gulf of America. The state-of-the-art ocean observing technologies are available for inclusion in cutting-edge machine learning, artificial intelligence, and modern data science methodologies to improve the predictive capability of ocean models.

Observing Platforms

Ocean Buoyancy Gliders

Ocean buoyancy gliders (Testor et al., 2019) provide vertical profiles of collocated temperature, salinity, and current velocity to 1000-m depth up to several times per day (depending on depth of profile and environmental factors that can impact vehicle flight characteristics). The glider models used in MASTR are Slocum gliders (Models G2 and G3, Teledyne Webb Research) and Seaglider (Kongsberg). A total of four ocean buoyancy gliders were deployed for the MASTR experiment. These deployments targeted the hydrographic structure of the western Caribbean Sea as waters entered the Yucatan Strait and the southeastern Gulf of America. The planned deployment duration for the MASTR gliders is 90 days (lithium battery power carried by the glider limits missions to up to 90 days). Lithium batteries allow for extended sampling, long transits, and travel to recovery sites. The extended configuration of the LC led to focusing the glider deployments initially in the western Caribbean Sea.

Slocum G3S Glider *RU-38* with 1000-m capability is owned and operated by Rutgers University. Slocum

G2 Glider Unit 540 (*Stommel*) with 1000-m capability is owned and operated by Texas A&M University. Eight Seagliders (Model M1) with different configurations are owned and operated by CICESE's fleet.

Near-Surface (Drogued) Drifters

Far Horizon Drifters (FHDs) are air-deployable satellite-tracked surface drifting buoys built and operated by Woods Hole Group (WHG). FHDs are equipped with either a 20-m or 45-m drogue to drift with the upper ocean currents and a 3-month battery supply. Drifters report GPS positions in real time, which are processed to provide Lagrangian estimates of near-surface current velocity (using differential positioning of the drifter) (DiMarco et al., 2005; Storie et al., 2023). Industry deployed surface drifters (e.g., FHDs deployed regularly since 1984 as part of WHG's EddyWatch ocean current monitoring and forecasting service for operators in the deepwater Gulf of America) have established the industry standard for metrics associated with Gulf of America LC and LCE dynamics, position, magnitude, and intensity. For details and specifications of these platforms, see <https://ieeexplore.ieee.org/document/5663921>.

High-Frequency Radar

Since June 2022, a high-frequency radar (HFR) system (Codar Seasonde, operating frequency is 5 MHz) deployed at two locations on the eastern Mexico coast (Quintana Roo, Puerto Morelos, and Isla Contoy) has provided hourly estimates of near-surface current velocity (6-km grid) across 70% of the Yucatan Channel and effectively captured the magnitude and variability of the velocity core of the Yucatan Current (precursor to the

LC and eventually the Gulf Stream) as it enters into the Gulf of America. When coupled with other HF radar observations from the Florida Straits, the HFR network of the southeast Gulf of America provides valuable surface current measurements, with quality controlled radial data available from the operators for data assimilation or numerical model skill assessment. The HF-radar data collected from the in-flow region of the Gulf of America through the Yucatan Channel provide the first near-real-time observations of the surface currents and their variability into the basin.

APEX Floats

One APEX-EM float was planned for deployment in the Yucatan Current. Float measures the temperature, conductivity, pressure, and velocity profiles from the surface layer to as deep as 2000 m. Logistical challenges presented by exporting and shipping this system to Quintana Roo prevented the planned deployment. Therefore, there was no deployment of the APEX-EM float during MASTR.

ROCIS Flights

The Remote Ocean Current Imaging System was developed by Fugro and technology partner Areté Associates and was deployed during MASTR. ROCIS is deployed with an aircraft. In this case, a total of five missions were flown over the Yucatan Strait and over the HF radar system pattern. ROCIS uses a combination of digital camera technology and highly accurate positioning systems, together with advanced algorithms, to derive surface currents from wave spectra measurements. In this case, the data and comparisons

with HF radar are the subject of another manuscript in development.

Timeline of Operations

Initial discussion and experimental design considerations for the MASTR experiment started long before the field deployment and data collection. To comply with international standards, ensure transparency, efficiently engage the international community, and maximize the collection and dissemination of high-quality data, the timeline for the MASTR experiment consisted of four phases.

- Phase 1: Diplomacy, September 2022 to December 2023
- Phase 2: Mobilization, December 2023 to January 2024
- Phase 3: Operations, 18 January 2024 to 1 May 2024
- Phase 4: Analysis. May 2024 to May 2026 (projected)

Phase 1: Diplomacy

Phase 1 was principally active from September 2022 to December 2023, i.e., prior to field operations. During Phase 1, the MASTR team communicated with the U.S. State Department and the Mexican and Cuban Consulates to submit required international research applications, to secure all necessary permissions, manage expectation, and define the scope of the research (including data access, geographical limitations, start/stop dates, durations, environmental parameters measured, and sampling metrics [e.g., sampling interval and frequency]). Elements of Phase 1 extend into Phase 3: Operations (described below) because of notification requirements to inform domestic and foreign authorities when MASTR platforms pass in and out of non-U.S. exclusive economic zones (EEZs).

Phase 2: Mobilization

During Phase 2, instrumentation platforms were prepared for deployment. Activities included scientific sensor calibration, instrument refurbishment, ballasting diagnostics, system diagnostics and power supply servicing and maintenance. Observation platforms were shipped to the final deployment destination of Puerto Morelos and Chetumal, México using domestic and international service providers. Phase 2 involved personnel from each institution and occurred in Fall/Winter 2023. Some logistical considerations during Phase 2 were necessarily delayed until diplomatic permissions were granted under Phase 1 activities. Data-flow pathways were tested and, in some cases, established to ensure end-to-end continuity of collected data to accessible data servers and federal (data assembly centers) and international (global telecommunications service) access points.

Phase 3: Operations

The field campaign was operational during Phase 3 of MASTR. Operations included the deployment and recovery operations of each platform. Most deployment and recovery operations proceeded with the use of small local commercial fishing vessels and dive boats. In this way, local expertise and indigenous knowledge were used to ensure safe and efficient action. While deployed, guidable instrument platforms, i.e., gliders, floats, and airborne instruments (ROCIS), were piloted by the responsible team members. All near-real-time data transmissions were monitored and assessed for quality. Active piloting was coordinated using web tools and services designed for voice and data communications and sharing.

Phase 4: Analysis

Following the operations phase, the team will be engaged in the processing, analysis, synthesis, and archival of data, data products, and numerical output. The timeline for analysis is to coincide with the in-situ field program and will provide guidance for the Grand Adaptive Sampling Experiment (GrASE) now tentatively scheduled for deployment in 2025. The timing, location, and duration of GrASE is currently (July 2024) under discussion. The best practices and lessons learned during MASTR are expected to be directly applied to the planning and operations for GrASE.

Below was the timeline for field operations and equipment deployment/recovery during Phase 3:

- 18 Jan 2024: CICESE *SG625/SG652*: deployed
- 28 Jan 2024: Rutgers *RU38*, TAMU *Stommel*: deployed
- 27 Feb 2024: CICESE *SG625*: recovered
- 04 Apr 2024: *RU38*: recovered
- 23 April 2024: *Stommel*: recovered
- 02 May 2024: CICESE *SG652*: recovered

All gliders and drifters were deployed and recovered within the Mexican EEZ. All data were collected within the Mexican and Cuban EEZs. Three thousand eight hundred eighty-seven (3,887) ocean profiles up to 1,000 m were collected. Glider tracks, based on GPS location at each glider surfacing, are shown in Figure 1. Collectively, the gliders transect a distance greater than 6,600 km. Each time a glider crossed into or out of the Cuban EEZ, officials in the U.S., Mexico, and Cuba were notified. Additionally, emails were sent periodically (12 emails between 18 January 2024 and 1 May 2024) during the experiment to these officials

to inform and update the status of the glider operations.

Water parameter profiles are collected on downward and/or upward trajectories, to 1,000 m or maximum water depth if less than 1,000 m. Profiles (down/up) typically take around 3 h and cover 1–2 km. Exact times, depths, locations, parameter values, and other metadata are available from the U.S. Integrated Ocean Observing System [IOOS], Data Assembly Center [DAC] ERDDAP server, as described later.

Near-Real-Time Communication of Experiment Progress

Multiple channels of communication were maintained internally (scientists, investigators) and externally (U.S. State Department, foreign officials) to apprise interested parties, stakeholders, team members, and the general public at large the progress and status of operations during the field campaign.

Results

Glider Observations Summary

The following tables (Tables 1 and 2) and graphics (Figures 1 and 2)

summarize the autonomous buoyancy vehicle and surface drifter data collection during the MASTR experiment and field program. Four gliders were deployed for a total of 298 days. While deployed, the gliders transited more than 6,600 km (roughly the radius of the Earth) and recorded nearly 3,900 vertical profiles of temperature and salinity.

Table 1 summarizes the four gliders deployed during the MASTR experiment in the Yucatan Channel. The table is categorized into start/end dates, number of days active, distance traveled, number of temperature and salinity profiles collected, mission status, and number of profiles with data quality metrics to post on the Global Telecommunications System.

The tracks shown in Figure 1 show the location of the four MASTR gliders from 19 Jan 2024 through 2 May 2024. Each glider is represented by a different color in the figure. The thin red line shows the boundaries of relevant EEZ of western Caribbean Sea countries. The tracks show that the gliders spent the majority of the time in the Mexican EEZ, east of Cozumel

and north of Chinchorro Bank. Three glider tracks moved into the Cuban EEZ for durations of roughly 5 days each.

Drifter Deployment Summary

Ten FHD surface drifters were vessel-deployed during MASTR. The four early drifters had 50-m drogues, while the later units had shorter 20-m drogues to prevent groundings. The two initial units were released during the glider deployment trips, south of the HF radar footprint. The main objective was for these drifters to sail through this area and provide data to perform intercomparisons with other platforms. Two additional units were deployed north of Cozumel, and the remaining were released at the eastern and western sides of Arrowsmith Bank. This later deployment was aimed at confirming early HF radar observations of the effect of the Bank in the regional flow variability. These drifters continued sailing north into the Gulf of America, delineating the extent of the LC and some adjoining cyclonic features. Figure 2 depicts the trajectories followed by the FHDs, and Table 2 provides a summary of the deployment.

TABLE 1

Glider summary statistics.

Glider Operator	Glider Name	Glider WMO ID	Start-End 2024	Days	Dist. (km)	DAC Profiles
CICESE	SG625	8901011	01-18	40	731	428
			02-27			
CICESE	SG652	8901010	01-18	105	1762	935
			05-02			
Rutgers	RU38	8901018	01-28	67	1,842	1,259
			04-04			
TAMU	Stommel	4801916	01-28	86	2,283	1,265
			04-23			
Total				298	6,618	3,887

Dist., distance.

FIGURE 1

Map of Yucatan Channel region of the western Caribbean Sea and southeastern Gulf of America showing glider tracks of CICESE gliders (*SG652* and *SG625*), Rutgers glider (*RU38*), and Texas A&M glider (*Stommel*) during the MASTR experiment from 18 January 2024 to 2 May 2024. Tracks are determined from GPS location data reported by the gliders at each glider surfacing. Tracks are color coded by glider: *Stommel*, purple; *RU38*, orange; *SG625*, blue; *SG652*, green. Red lines indicate boundaries of regional EEZs for western Caribbean Sea countries. Blue shading indicates water depth in meters.

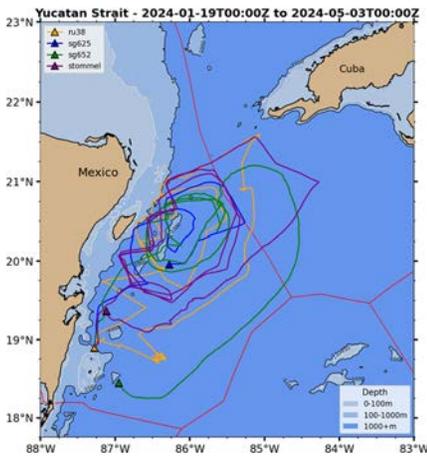


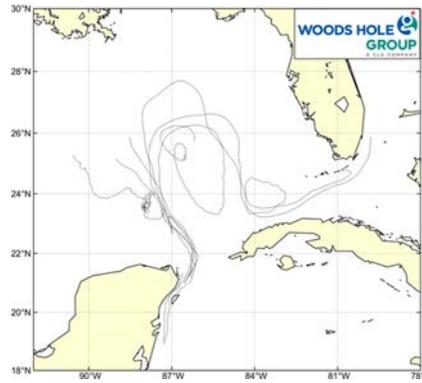
TABLE 2

Surface drifter summary.

Drifter ID	Date	Days Reporting	Deployment Latitude	Deployment Longitude
8957	01-18	4	18.9943	-87.2574
8955	01-28	5	18.8913	-87.2736
8954	02-20	0	20.6193	-86.7085
8956	02-20	71	20.6067	-86.726
9630	06-02	47+	21.1859	-86.4041
9711	06-02	24	21.1822	-86.5214
9652	06-24	18	21.0000	-86.5833
9712	06-24	19	20.9333	-86.3833
9713	07-14	5+	21.0000	-86.5833
9714	07-14	5+	20.9333	-86.3833

FIGURE 2

Map of southeastern Gulf of America and western Caribbean Sea showing surface drifter tracks deployed during MASTR (Jan-Jun 2024).



Oceanographic Conditions in January 2024

At the beginning of the intensive field campaign (mid-January 2024), the Yucatan Current speed core occupied the western half of the Yucatan Strait. The LC was in an extended configuration into the Gulf of America (northward extension to about 26°N). As seen in Figure 3, an LCE, nick-

named Eddy Berek, had separated from the LC stem and migrated westward with the center of rotation near 26°N, 89°W. Northwest of Cuba, the surface circulation between the LC and the island forms a closed circulation cell. Eddy Berek had undergone several transitions from separation in mid-2023, to reattachment, and separation in the latter period of 2023 and early 2024. During the MASTR period, a newly detached eddy, Eddy Cardone, dominated the current regime of the eastern Gulf of America. Several smaller cyclonic eddies (CEs), counterclockwise rotating circulation, were present along the periphery of the LC. The CEs tend to evolve spatially and temporally and intensify and weaken throughout the experiment.

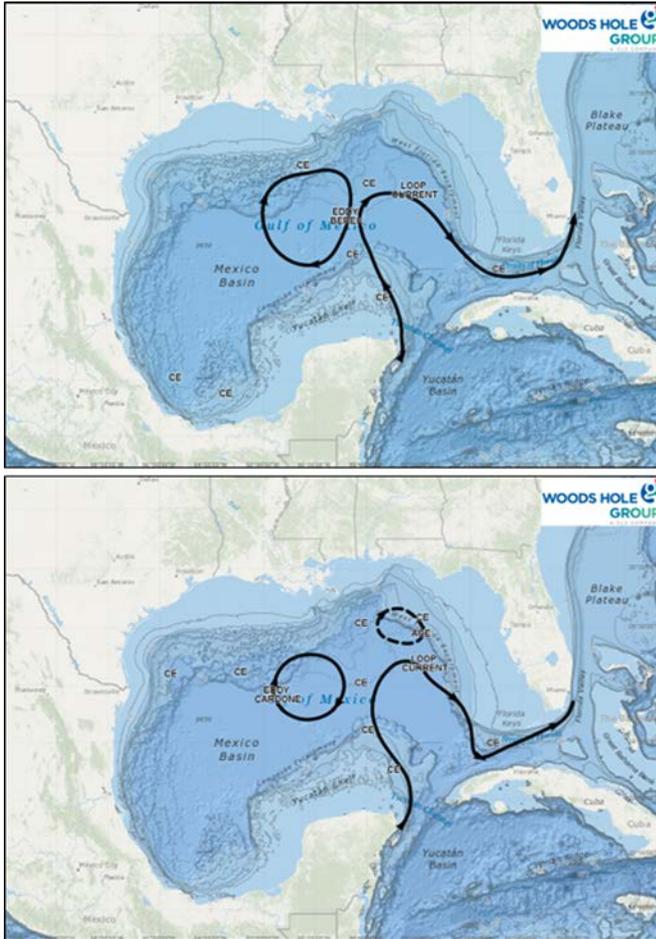
Glider Observations

During MASTR, several transects have been carried out along the Yucatán Current with the *SG652* glider as well as in several structures present in the region. Stream transects were characterized by an oscillation of isotherm depth between cyclonic (shallower) and anticyclonic (deeper) circulation regimes. This typical effect can be observed up to ~800-m depth within anticyclonic structures in the region, as clearly seen in Figure 4 (top). During the experiment that lasted ~3.5 months, we were able to observe a 1°C increase in surface temperature (from ~28°C in January to ~29°C in May). At depth (~1,000 m), the observed temperature was ~5°C, which is the typical temperature of the deep Caribbean Sea.

In Figure 4 (bottom), the Hovmöller plot for the salinity along the *SG652* trajectory is shown. Typically, different water masses can be distinguished through their salinity values, and the

FIGURE 3

Configuration of the LC system in January 8, 2024 (upper panel) and May 15, 2024 (lower panel) as defined by the 1.5-kt isotach (WHG Frontal Analysis).



salinity is quietly connected with the temperature field where both cyclonic/anticyclonic structures can be easily identified within vertical oscillations. At the surface, Caribbean Surface Water can be easily identified by its lower salinity values compared with the Subtropical Underwater (STUW) that lies just beneath and is characterized by the salinity maximum that can reach values > 37 PPT between 150- and 200-m depth. At deeper waters (> 300 m), Sargasso Sea water, Tropical Atlantic Central Water, and Antarctic Intermediate Water can be found (see Figure 8 for reference).

The temperature-salinity scatterplot for *Stommel* as a function of the mission timeline is shown in Figure 6. All water masses are indicated for reference. It can be noted that cooler and colder waters are found at the beginning of the mission near the coast just north of the Chinchorro Bank. Likewise, some variability can be noted in the STUW certainly associated with the presence of mesoscale structures in the region.

The 3-D plot in Figure 7 shows the spatial distribution of temperature and salinity in the western Caribbean Sea and Yucatan Channel during MASTR. The plot is a composite of

all glider missions. The orientation of the plot is looking north from the Caribbean towards the Gulf of America. The land masses of Cuba and the Yucatan Peninsula are seen on the right and left sides of the graphic, respectively.

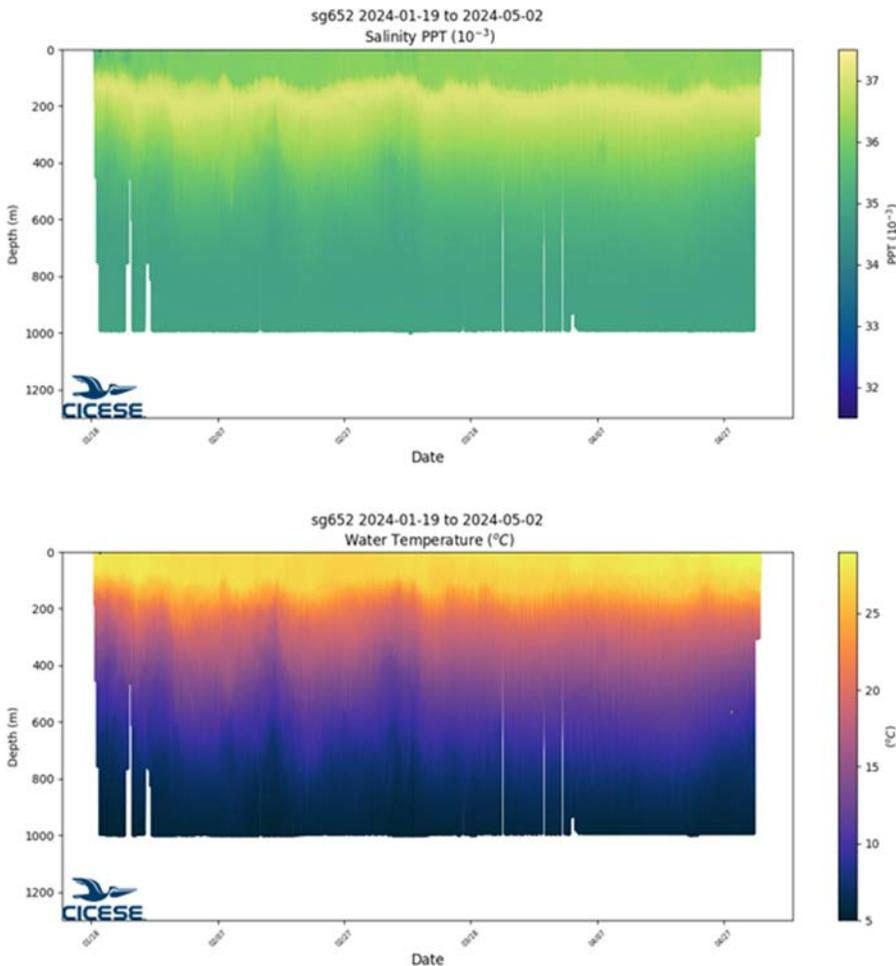
In the top graph, warmer temperatures at the surface are lighter colors, and cooler temperatures at depth are dark. The plot emphasizes and reinforces the spatial variability of the temperature in the waters of the western Caribbean and its relation with proximity to land. The salinity data (bottom figure) show the spatial distribution and variability of salt in the region. The lighter (yellow) colors depict high salinity; evident in this graph is the presence of relatively high-salinity subsurface water, representative of the STUW flowing through the Caribbean Sea from the subtropical Atlantic Ocean.

From the scientific perspective, understanding the relationship of temperature and salinity in the ocean and particularly how this relationship varies with depth and proximity to the coastline is believed to be a critical factor to improve numerical prediction of the ocean environment. The research underscores the complexity of the four-dimensional structure of the LC system and the spatial and temporal evolution of the circulation in response to topographic, tidal, geostrophic, ageostrophic, and wind forcing.

The MASTR experiment incorporates the use of several agency and industry numerical models to guide the observing assets during deployment. Priority is given to position and direct mobile platforms to regions of high variability. However, caution is also advised due to the potential for current speeds to far exceed the forward

FIGURE 4

Hovmöller plots (date: x-axis, depth: y-axis) showing temporal evolution of temperature (top: color bar, °C) and salinity (bottom: color bar, ppt [practical salinity]) observed by *SG652* during MASTR.



speed of the gliders, which makes arbitrary navigation difficult. Additionally, the presence of submarine obstacles in the form of shallow banks and reefs further complicates piloting operations (Figure 5).

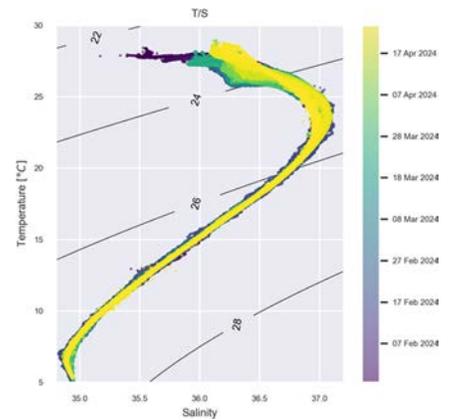
The numerical output is also available to provide context to the observations and to assist with interpretation. Four operational models are available for direct comparison of MASTR observations. NOAA's Global Real-time Operational Forecast System (RTOFS), the U.S. Navy Global Ocean Forecast System (GOFS 3.1), and the European Copernicus Marine Environment

Monitoring Service (CMEMS). We also have access to three higher resolutions models, the Navy's intra American Seas model, the North Carolina State University Coupled Northwestern Atlantic Prediction System, and the WHG Tendral Ocean Prediction System model.

Observed vertical profiles collected by the gliders and floats of temperature, salinity, and density are made available and displayed on multiple websites and include the glider data portals maintained by GCOOS (gandalf.gcoos.org) and NOAA's National Glider DAC. The observed

FIGURE 5

Temperature-salinity (T/S) scatterplot of all observations enhanced by the *Stommel* during MASTR. The colors represent the gliders' mission timeline.



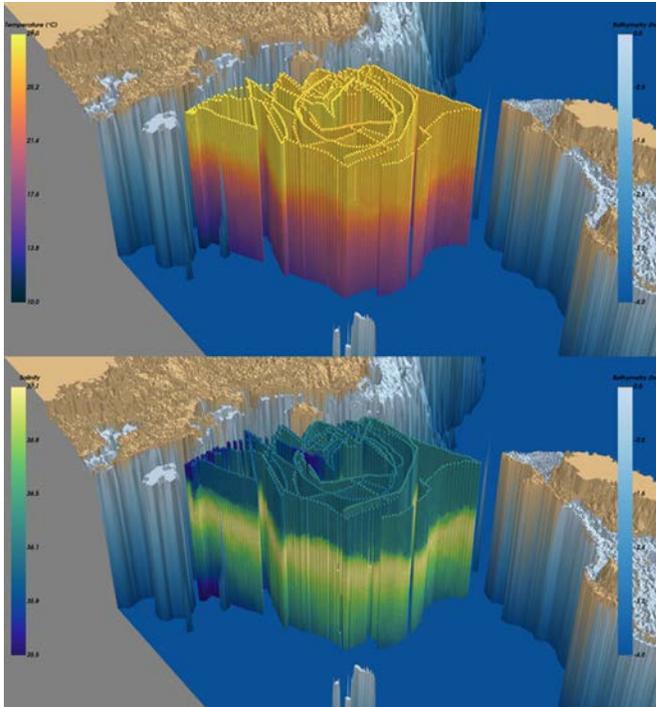
profiles are plotted against vertical profiles of similar variables extracted from CMEMS, RTOFS, and GOFS as maintained by the U.S. IOOS Hurricane Glider consortium (Figure 6).

Impact of Glider Observations on Ocean Forecasts

The sequence of graphics shown in Figure 7 displays the impact of glider observations on numerical model output in the MASTR region at the beginning of the experiment (late January 2024). Vertical profiles of temperature (left), salinity (center), and density (right) in the upper 1,000 m are provided for the glider (blue) and three numerical models (NOAA RTOFS: red, U.S. Navy GOFS: green, and the European Union CMEMS: magenta). The numerical model output is provided for the closest model grid cell to the observation locations at the time of the observations. The glider observations represent the average (dark blue) of nine individual profiles (light blue). The subsurface maximum salinity associated with the movement of STUW formed in the Atlantic Ocean is prevalent between

FIGURE 6

Three-dimensional plot of Yucatan Channel region during MASTR showing temperature (top) and salinity (bottom) spatial variability. The perspective shown is from the Cayman Sea and looking northwest into the Yucatan Channel and Gulf of America. Cuba is seen as the land mass on the right of the graphic; Quintana Roo, Mexico, is to the left. Depth is limited to the upper 1,000 m of the ocean.



100- and 200-m depth. Prior to glider observations assimilation into the numerical models (Figure 7, top), it is seen that the three models are cooler than the glider observations, particularly in the depths between 50 and 175 m. The difference in observations is significant in the salinity profiles at these depths, with RTOFS and GOFS models up to 1.5 salinity units fresher between 50 and 350 m.

The impact of the glider observations on the ability of numerical models to accurately represent the salinity structure of the Caribbean basin as the water enters the Yucatan Strait and flows to the Gulf of America is shown in Figure 9 (bottom). The close alignment of property profiles for CMEMS to the glider observations reveals that both Subtropical Underwater [STUW]

from the NOAA RTOFS and GOFS models are fresher and cooler than the observations prior to the assimilation of the glider observations. After glider observations are assimilated, the numerical models are significantly improved. The implications downstream (into the Gulf of America and beyond, i.e., into the Gulf Stream) of this difference on ocean dynamics and climate are currently being assessed.

HFR Observations

An HFR system has been collecting hourly near-surface current velocity estimates in the Yucatan Channel. The system operated continuously during the entirety of the MASTR experiment. Figure 8 shows a representative horizontal surface current map on 20 February 2024 0800 UTC with color contours

indicating the current speed and streamlines representing the current direction. The HFRs were deployed to optimize coverage of the high-velocity core of the Yucatan current as it flows northward into the Gulf of America. HFR receiver antenna patterns were calibrated using Automatic Identification System [AIS]-derived shipboard locations. Both radial and total vector data were quality controlled using the full IOOS QARTOD manual with Quality Control [QC] flags appended to each file. Hourly data from the HFR are used to map the current field and provide guidance to glider operators and drifter deployments, intercomparisons between HFR and ROCIS surface currents, and assimilation by the models.

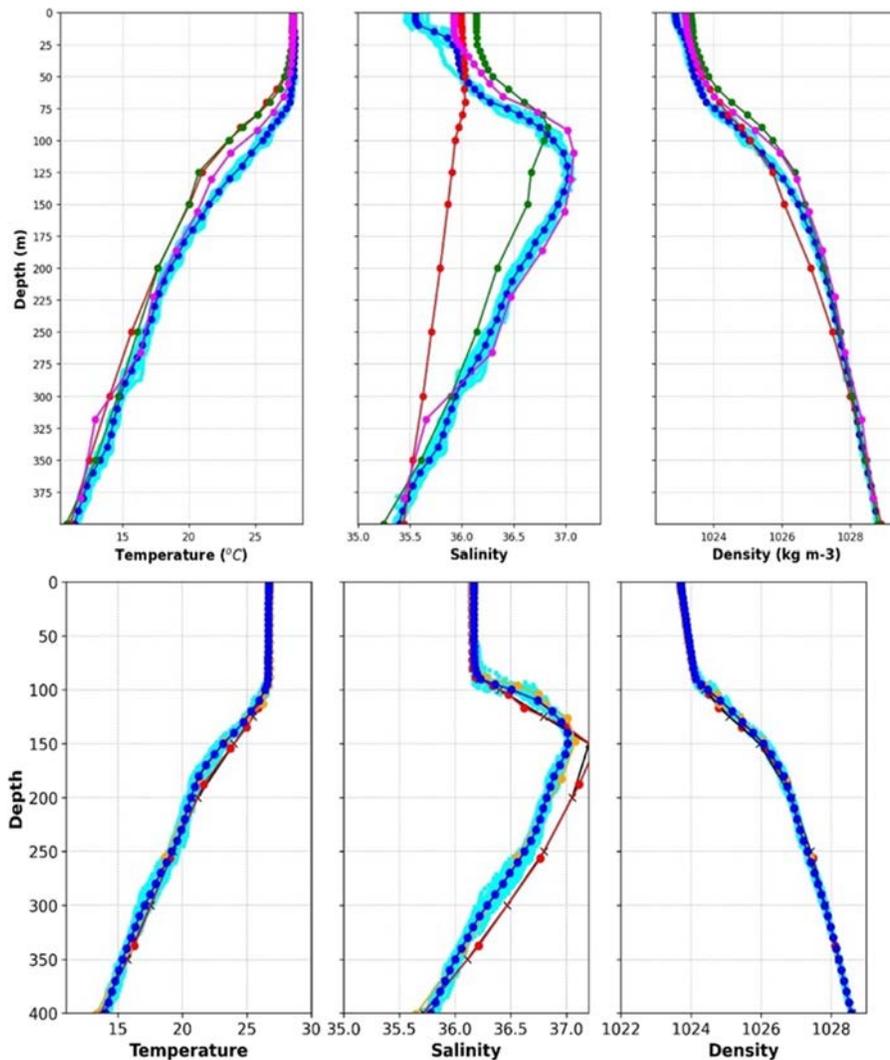
Observations from the HFR are shown in Figure 9. The left set of panels shows statistics and observations of the along-channel velocity component, and the right set shows the cross-channel velocity component. The data are for a full 1-year period (April 2023 to April 2024). The panels at the bottom of the figure represent the temporal mean of each of the velocity components. The thin panels to the left of the Hovmöller graphs represent time history of the spatial mean across the channel.

The red colors of the along-channel velocity indicate a predominantly northward flow into the Gulf of America. However, on the eastern channel, along-channel velocity tends to be weakly southward. The temporal mean (bottom left) shows the western channel intensification of the Yucatan Current with a maximum mean velocity west of Arrowsmith Bank (northeast of Cozumel) at about 1.2 m/s.

The cross-channel velocity is more variable. The blue shading of the

FIGURE 7

(Top) Before glider data assimilation into numerical models. Average of 10 vertical profiles of temperature, salinity, and density from glider *SG652* (blue) (20 January 2024) and nearest neighbor profiles from NOAA RTOFS (red), GOFs (green), and CMEMS (purple) numerical models. (Bottom) After glider data assimilation into numerical models. Average of 10 vertical profiles of temperature, salinity, and density from glider *RU38* (blue) (28 February 2024) and nearest neighbor profiles from NOAA RTOFS (red), NOAA RTOFS Parallel (orange), and CMEMS (purple) numerical models. Graphics from GANDALF.GCOOS.org, CICESE, and the IOOS Hurricane Glider consortium.

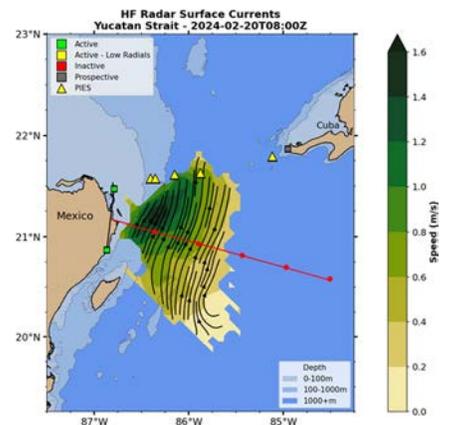


cross-channel velocity indicates predominantly westward-flowing currents resulting from the dominantly easterly winds of the channel. However, at the longitude of Arrowsmith Bank, the cross-channel currents are interrupted and episodic with frequent reversal to eastward currents. This is reflected in the temporal

mean cross-channel currents as a distinct velocity minimum at 86.5°W (lower right panel). In the far east, occasionally strong eastward cross-channel flow indicated in red can be associated with storms like Hurricane Idalia (late August 2023). This is also generally seen in the far eastern side of the diagram and is confirmed in the

FIGURE 8

Map of Yucatan Channel region showing surface current velocity observations recorded by Yucatan HFR system deployed in Quintana Roo, Mexico. Date of observations is 20 Feb 2024 0800 UT. Green squares indicate locations of radar units: ISCY (north) and UASA (south). Yellow triangles indicate locations of subsurface profiling inverted echo sounders (PIES). Red line indicates the optimal transect with the highest quality data, with circles every 50 km.

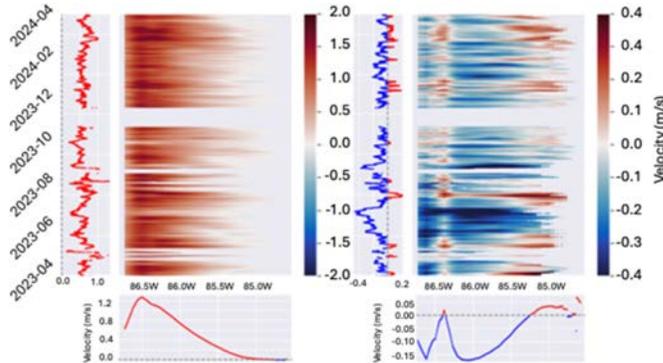


temporal mean cross-channel velocity as predominantly east-flowing currents east of 85°W.

The complicated dynamics of the western Yucatan Channel is also indicated in the historical record of the global surface drifter program (DiMarco et al., 2005; Elipot et al., 2022) and shown in Figure 10. Here, the trajectories of 163 Global Surface Drifter [GSD] platforms that passed the Yucatan Channel between 1979 and 2022 are categorized by color, with blue shades indicating the drifter passed between the Mexican mainland and Cozumel; orange color indicating the drifter passed between Cozumel and 86.5°W, i.e., west of the island; and green referring to all other drifters passing through the Yucatan Channel. Therefore, the island of Cozumel and system of downstream banks that includes Arrowsmith Bank are seen to strongly influence

FIGURE 9

Hovmöller diagrams of the along-channel current component (left, positive to north) and the cross-channel current component (right, positive to east) along the optimal red line in Figure 8 from April 2023 through April 2024. Figures along the left of each Hovmöller are the time series of velocity integrated along the red line. Figures along the bottom of each Hovmöller are the velocities integrated in time for each grid point along the optimal red line. Note the change in scale range for the along- and cross-velocity components.

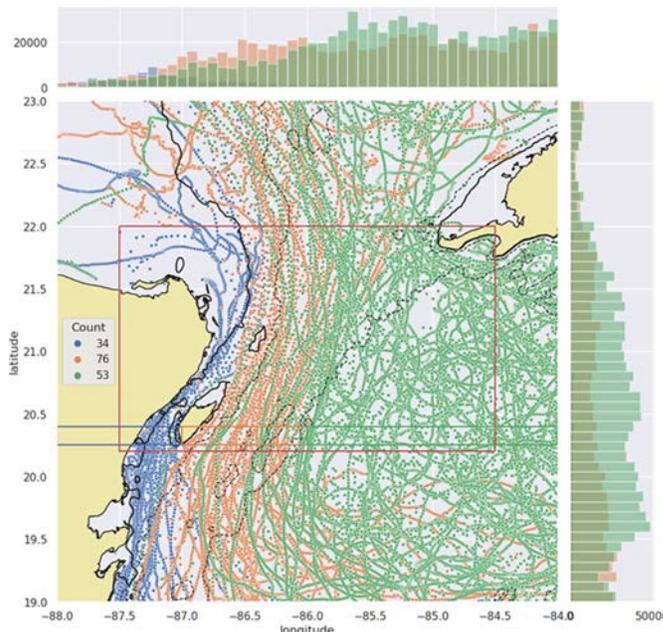


downstream current characteristics. Surface drifters that pass through Cozumel Strait remain on the western side of the Yucatan Channel and west

of Arrowsmith Bank, while surface drifters that pass the west coast of Cozumel tend to remain to the east of Arrowsmith Bank. Additionally,

FIGURE 10

Map of western Caribbean Sea and Yucatan Channel region showing global surface drifter program tracks (Elipot et al., 2022) and used in DiMarco et al. (2005). Shown are all tracks that passed through the Yucatan Channel between 1979 and 2022. Track colors indicate drifters that passed through the Cozumel Strait (between Cozumel and the mainland), between 86.5°W and Cozumel (orange), and all other drifters (blue). The histograms to the right and top of the graph indicate the total number of observations in each degree band.



there are few drifter observations directly above the Arrowsmith Bank.

Therefore, the drifter observations (Figure 10) and the HFR observations (Figure 9) are complimentary evidence of a surface current bifurcation and associated shadow zone at the longitude of Arrowsmith Bank.

Decision Support Tools

The tools of combined uncertainty and reachability maps as piloting aides of mobile platforms under environmental stresses are assessed in the context of optimization of trajectories. This subject is addressed in Lermusiaux et al. (2024) and Mule et al. (2024).

Collaboration and Future Activities

The principal investigators would very much like to make contact with regional scientists or representatives of interested national agencies with whom we can arrange similar activities.

Transition to Operations

The knowledge, data products, and decision support tools described here and developed during this experiment are expected to be transitioned into routine and widely available operational services. Ultimately, the findings of MASTR, and the follow-up experiment GrASE, and other activities of the UGOS program will inform future prediction system development and will guide additional transition to operations. Clear communication pathways among implementation teams and coordinated integration of observations, forecasting systems, and products are needed to ensure that the stakeholder

requirements and expectations are met. As the example described in this paper demonstrates, products and services can be developed that meet the specific needs of a large range of stakeholders and users, which include industry, government agencies, scientific community, and the general public.

MASTR Evolution to GrASE

The lessons learned and best practices developed during MASTR are expected to guide the planning of the GrASE experiment, which is tentatively scheduled for early summer 2025. It is anticipated that the number and variety of observational platforms will increase during GrASE. New observing platforms, e.g., the Surface Water and Ocean Topography [SWOT] satellite of high-resolution altimetry, are expected to become fully operational for GrASE. It is also expected that the spatial resolution of some numerical models will improve to ~1 km. Also, Lermusiaux et al. (2024) and Mule et al. (2024) have developed statistical models that can optimize the trajectories of adaptive observational platforms and address the issue of reachability for slowly moving platforms in a swiftly moving environment, e.g., estimating the probability that a glider can reach a destination in a specific time given the speed of the glider and speed of the current.

In the coming months, the GrASE team will outline the tasks necessary to plan and execute the experiment. The planning will follow the four-phase protocol developed during MASTR. Most importantly, the diplomatic phase will require early identification of all instrument platforms and sensor types that will be deployed so that research applications in foreign waters can be submitted to ap-

propriate consulate offices and embassies. This step, we have found, is critically important and is the single-most controlling factor for the timing and execution of the research plan and guides the success of the research outcomes.

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