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Quo Vadimus

A framework for multidisciplinary science observations from commercial ships

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Abstract

Science Research on Commercial Ships (Science RoCS) is a grassroots multi-institution group of scientists, engineers, data managers, and administrators seeking to further research opportunities by equipping commercial vessels with suites of maritime appropriate scientific sensors operated autonomously on regular ship routes with minimal crew intervention. Science RoCS aims to foster cooperation between the shipping industry and scientific community at a level that will be transformative for societally relevant ocean science, promote cross-disciplinary ocean science through simultaneous observation of the air/sea interface and water column, and spur a technological revolution in observational oceanography by developing new turnkey, maritime-industry-appropriate scientific equipment whose data streams can be used to stimulate innovations in oceanic (physical, chemical, and biological) understanding and forecasting. We envision a future where scientific data collection on commercial ships is the new industry standard, providing repeat measurements in undersampled, remote regions, on scales not otherwise accessible to the scientific community.

Keywords: instrument platform; sustained observations; multidisciplinary; industry partnership; ocean measurement; atmosphere measurement; marine observation

The vision: science–industry partnerships for the future of ocean observation

Repeat observations that transect strong currents, cross the transition between open ocean and shelf regions, and sample remote basins are imperative to understanding how the ocean's physical, chemical, and biological cycles are evolving on the backdrop of a changing climate. Such time series observations are foundational for both direct analysis and numerical simulation (predictions and reanalyses); however, they are difficult and expensive to obtain and maintain.

Over the past 100+ years of collecting *in situ* observations from ships, oceanographers have been able to directly access <20% of the global ocean (National Ocean Service, 2023). Satellites and drifting buoys have provided decades of surface observations and profiling floats have greatly increased the density of upper water column temperature/salinity profiles. The recent advent of Deep Argo (2023) will eventually fill the gap in deep ocean observations, while SOCCOM (2023) and GO-BGC (2023) are beginning to provide improved temporal and spatial biochemical resolution. Meanwhile, direct subsurface observations of ocean currents and biological and biogeochemical water column characteristics lag behind, remaining vastly undersampled in both space and time, thereby limiting scientific breakthroughs and solution-oriented research.

Ships of opportunity provide improved access to the undersampled ocean beyond what research vessels can cover. The World Meteorological Organization (WMO 2023) and United States Voluntary Observing Ships program (VOS 2023) operated by the National Oceanic and Atmospheric Administration (NOAA), and the Ship of Opportunity Programme (SOOP 2023) established by the Global Ocean Observing System (GOOS 2023) support shipboard meteorological weather stations, the global eXpendable bathythermograph (XBT, a probe that provides a profile of temperature down to ∼750 m depth) and pCO_2 programs (Ocean Carbon Network 2023, XBT Network 2023), and on occasion, underway sampling and autonomous sensor deployments. These efforts are broad in scope, and some are interdisciplinary, but they are a challenge as they require personal attention and often a learning curve to find a vessel, set up the platform, obtain required clearances to collect observations in foreign waters legally, and maintain lines as vessels and routes change. Science RoCS seeks to facilitate a two-way connection between science and industry, to organize individual efforts, to provide observations in near-real time, and to provide underway data sets that benefit science, industry, and local communities

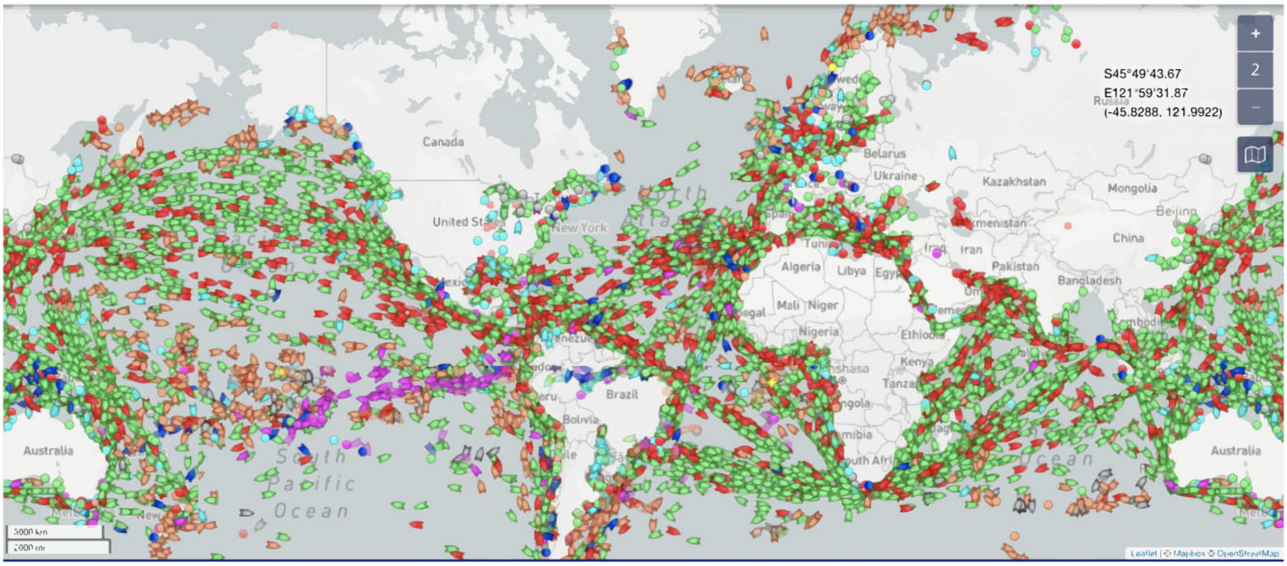

Figure 1. Example of commercial ship coverage: April 2023 snapshot of vessel locations (MarineTraffic 2023).

according to FAIR (Findability, Accessibility, Interoperability, and Reusability; Wilkinson et al. 2016) and CARE (Carroll et al. 2021) principles.

Availability of research vessels is inevitably limited, and while some ships of opportunity are being utilized for science, leveraging enduring partnerships with the commercial shipping industry could revolutionize the collection of oceanographic, meteorological, seabed, and climate data. With >50 000 commercial ships in operation today (Fig. 1), commercial shipping represents an existing "networked blue economy" (NSF 2022). This industry is facing the dual challenges of reducing operating costs while minimizing environmental impact to reach sustainability goals (e.g. Maersk Sustainability 2023, Stena Sustainability 2023, Wallenius-Wilhelmsen 2023). Industry is therefore eager to participate in ocean science efforts that can provide not only a greener image, but actual positive effects on cost, safety, and carbon footprint. While industry is brimming with opportunities for expanded partnerships (e.g. UNESCO 2021), <3000 commercial ships routinely contribute surface meteorological observations to support research and operational weather and ocean forecasting. Far fewer provide routine oceanographic data (Rossby 2011, Smith et al. 2019).

The history: building on success

Partnering with the shipping industry to obtain scientific observations is not new. A tradition of science and industry sharing oceanographic information and resources to arrive at science-based answers to societally relevant questions stretches from colonial times to today (Franklin et al. 1768, Richardson 1980, Rossby et al. 2014, 2019). In the modern ocean, commercial ships transmit near-real-time atmospheric data for weather prediction, and science riders (non-industry personnel who sail on a vessel, often students or technicians) support measurements to study carbon exchange and ocean acidification (Dickson et al. 2007, Sutton and Newton 2020, Wanninkhof and Pierrot 2020), as well as ocean heat content and change. Hull-mounted acoustic Doppler current profilers (ADCPs) that continuously scan currents in the upper kilometer of the ocean have become standard underway tools on research vessels (Firing and Hummon 2010, 2012) and a handful of commercial vessel owners have accommodated scientists' requests to install these ocean velocity sensors on container ships and ferries (e.g. Rossby and Gottlieb 1998). A related through-hull technology, split beam echosounders (Seaman 2024) that use active acoustics to scan the water column for biological studies, is also in use on commercial ships (Benoit-Bird and Lawson 2016, Howe et al. 2019, Haris et al. 2021).

The archetypical US-based integrated commercial ship observing platform that includes an ADCP is the *CMV Oleander* (Flagg et al. 1998, Rossby et al. 2019), which has been collecting underway velocity profiles in the Northwest Atlantic between New Jersey and Bermuda since 1992. With minimal interaction from the crew, underway surface temperature and salinity observations are also collected, along with discrete temperature profiles using an autonomous probe launcher directed by scientists on shore (Fratantoni et al. 2017). A continuous plankton recorder can also be deployed by the crew. The *Oleander* program has demonstrated the tremendous scientific payback that can be achieved with an integrated observing system on even a single commercial route. *Oleander* observations have been used to (i) validate satellite altimetry-derived surface geostrophic currents (Worst et al. 2014); (ii) assess how well Gulf Stream horizontal structure is represented in numerical models (Chi et al. 2018); (iii) study marine heatwave events on the Middle Atlantic Bight shelf (Gawarkiewicz et al. 2019, Perez et al. 2021); (iv) document long-term warming of subsurface temperatures on the continental shelf and upper slope (Forsyth et al. 2015); (v) uncover changes in the strength of the Shelfbreak Jet (Forsyth et al. 2020); (vi) examine acoustic backscatter from the ADCP as a proxy for biomass throughout the Slope Sea and Sargasso Sea (Palter et al. 2019); (vii) investigate submesoscale dynamics (Callies 2019); and (viii) demonstrate long-term stability of the Gulf Stream transport in the face of strong interannual and mesoscale variability (Rossby et al. 2014, 2019).

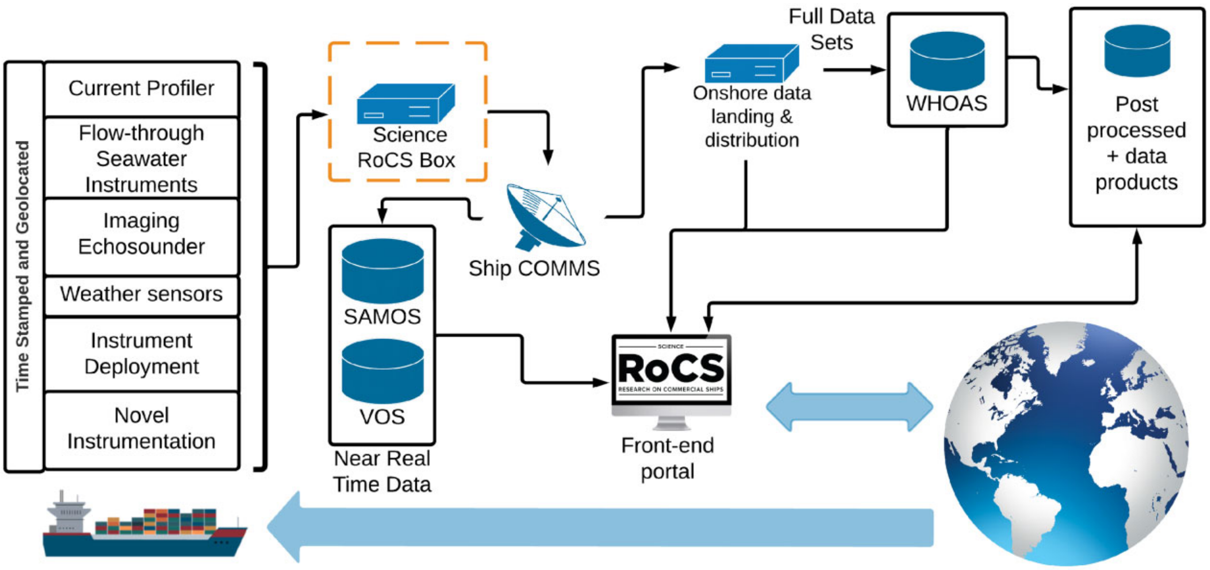

Figure 2. Schematic of envisioned Science RoCS flow: from a front-end portal connecting science to vessels and ship owners to science, to integrated data acquisition, to FAIR (Wilkinson et al. 2016) data. Here, science can include process studies, sensor developers and deployers, modelers, forecasters, emergency responders, those without access to research vessels, etc. WHOAS, VOS, and SAMOS acronyms are defined in the text with links in the reference section.

The strategy: facilitating science–industry partnerships

The *CMV Oleander* is a single ship example, a specific project (Rossby et al. 2022) that has been maintained for three decades through the efforts of a small, dedicated group. There are other examples of such efforts (ferries, cruise ships, other container vessels) that have acquired a variety of measurements. However, not all the data are of science quality, some are difficult to access, and often these efforts are stalled or ended due to a ship route change, a vessel retirement, a change of captain, loss of interest by a company, or an interruption in science funding. Science RoCS envisions a future where commercial ships are built instrument-ready and where a suite of scientific instruments installed and operating on new vessels becomes the industry standard. Envisioned as a facility, the future Science RoCS system has three interacting components that connect industry and science, facilitate continuity of measurements along scientifically valuable routes, and provide data to users. These are liaising, integration at sea, and post-processing.

Liaising

The framework (Fig. 2) centers on a front-end portal through which all users (scientists, industry, and stakeholders) can access the facility. Through the Science RoCS portal, a researcher proposing to collect a new physical, chemical, and/or biological oceanic or atmospheric data set would be guided to suitable commercial routes and would be provided with a clear roadmap for plugging into existing instrumentation, installing new or novel sensors, or arranging deployments of autonomous instruments from the ship. If no such vessel exists, a request could be submitted to have one found. Likewise, a researcher, perhaps a student or numerical modeler, seeking existing records could *easily* locate and *freely* read available single or multiple quality-controlled data sets located at national repositories, and simultaneously discover related publications. Should a clearance be required for sampling in foreign waters, this too could be handled by the front-end portal. Meanwhile, a shipping company seeking to host scientific equipment could reach out through this same portal to be connected with scientists seeking to use a vessel as an observation platform. Liaising will play a role in our growth. Science RoCS has made connections with the GOOS Ship Observations Team (SOT 2023) as well as other GOOS activities. As we expand, we will build our relationship through relevant GOOS teams and panels.

Integration at sea

A Science RoCS vessel is envisioned as an integrated observing platform that is designed to serve data from multiple instruments to a broad community of stakeholders onshore. Via a steering committee, users onshore could provide input to the platforms prior to sailing or in some cases while vessels are at sea (e.g. directing adaptive sampling strategies). Scientific sensors installed on a ship would be integrated by a data acquisition and control system, known as the RoCS Box. The RoCS Box is being developed to collect simultaneous science-quality data streams with minimal need for shipboard technical support and with only occasional crew intervention. It will allow for remote monitoring of sensor performance, switching data collection on/off remotely, and delivering data to servers onshore. Building on the progress in ocean data collection made by the innovators of the Ferrybox (2023), the RoCS Box will provide "plug and play" infrastructure that could support co-installation of a Ferrybox and support collection from a broad range of sensors, including but not limited to ADCPs, meteorological sensors, and marine radar.

Science RoCS together with the international GOOS Ship Observations Team intends to implement a sustainable data pathway for the incorporation of oceanographic, bathymetric, meteorological, and other data collected on participating commercial ships into the Global Telecommunication System (GTS) via the OpenGTS, and as the system matures, into the

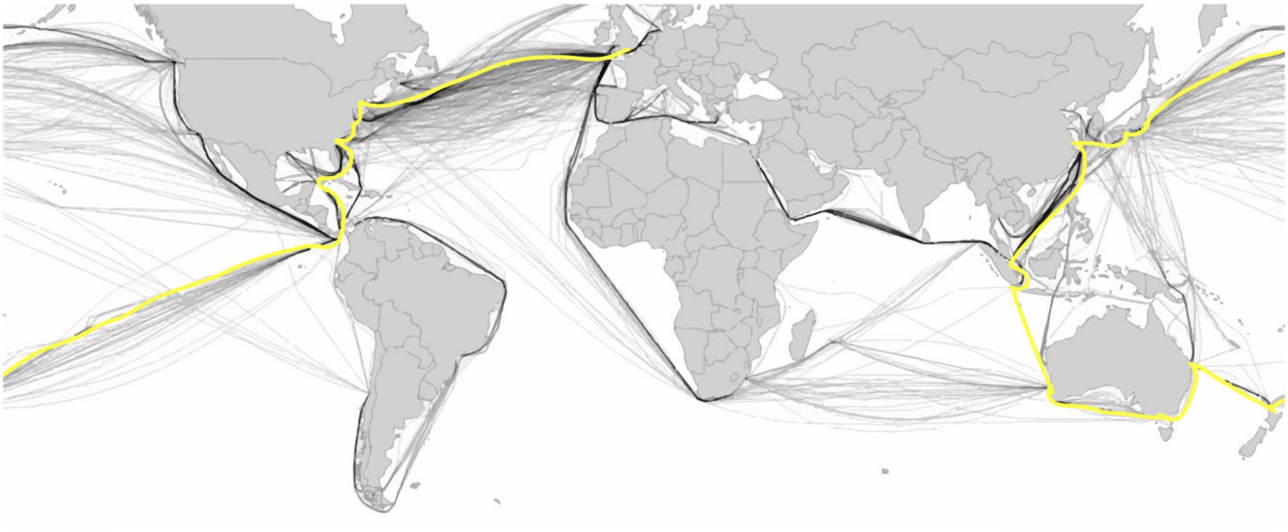

Figure 3. Map of Wallenius-Wilhelmsen ship tracks (gray curves) during a 6-month period in 2020. Science RoCS facilitated the Tysla (a vehicles carrier) pCO2 route which is highlighted (SMHI Weather Solutions image courtesy of G. Fagerheim).

next-generation WIS 2.0 (WMO Information System, second generation), thereby making near-real-time data available to, for example, ocean modelers and forecasters. The ship owners and operators will also have access to real-time *in situ* current measurements that can be used to save them time and fuel, thereby reducing costs and environmental impact.

Post processing

The post-processing component of Science RoCS focuses on moving all observations to locations where observations will be publicly available by providing a pipeline from the platforms to a broad user base beyond those who participated in the funding and installation of a specific instrument. So, along with near-real-time data, Science RoCS intends to provide delayed-mode data to appropriate distributions/archives, and to produce measurement-specific processed products. Particular post-processing and quality control, as well as the products that result, will be individualized to the sensor, but the concept is similar for all data sets with five defined levels of processing (*raw*, *onboard low-level auto-processed*, *onshore higher-level auto-processed*, *post-processed gridded*, and *derived products*), which are based on NASA's Earth Observing System Data and Information System data processing levels (Earthdata 2024). Science RoCS will work with others both in the USA and internationally to bring the relevant expertise to bear on post-processing of the expect variety of sensors.

First partnerships

There are presently three examples of Science RoCS partnerships that make best use of *in situ* multidisciplinary ocean/atmosphere observations to improve predictive capabilities for physical and biogeochemical trends and extreme events. We are actively engaged with industry partners Wallenius-Wilhelmsen and Pangaea Logistics Solutions Ltd, and various science partners to develop three pilot collaborations: (i) with the global Argo (2024) program to have commercial ships deploy profiling floats in locations research vessels rarely or intermittently frequent (Showstack 2021, 2022, Mkitarian 2023); (ii) with NOAA's Ocean Carbon Network (2023) installing a pCO_2 sensor on a ship that transits undersampled routes in the open ocean (Fig. 3, yellow highlight); and (iii) with Pangaea, developing their *MV Bulk Xaymaca* (Fig. 4b) as a showcase multisensor platform. The first two are examples of Science RoCS facilitating connections between science and industry. The third we describe in more detail.

Twice a month, the *Xaymaca* runs a regular route between Discovery Bay, Jamaica and Gramercy, Louisiana through the western Caribbean Sea and Yucatan Strait and across the Gulf of Mexico (GoM) and the US continental shelf, providing transects through a highly variable current system and an eddy-rich region. (Fig. 4c). At present, the ship is equipped with a Teledyne RD Instruments 75-kHz Ocean Surveyor ADCP and a Vaisala WXT-536 weather station (Fig. 4a). A website for data handling is under development and meteorological data are currently being sent to the OpenGTS. There is potential for a more diversified sensor package as well as a variety of associated delayed-mode products.

The *MV Xaymaca* was chosen for several reasons that illustrate the importance of a careful well-managed process for matching ships with science. The *Xaymaca* is a relatively young vessel, and in 2020 she was about to be refurbished to take over one of Pangaea's long-standing routes through the GoM. This ship's speed is generally less than ∼14 knots. The route crosses regions with high-science value and passes through territorial waters for which we requested and received official clearances for underway shipboard data collection through the US State Department. The CEO of Pangaea was extremely interested in bringing science onto his vessels. The planned drydock for the refurbishment of *Xaymaca* provided us with the opportunity to install a through-hull ADCP sensor and a weather station. The weather station data being sent to the OpenGTS will be evaluated by the Shipboard Automated Meteorological and Ocean Systems (Smith et al. 2018, SAMOS 2023). None of this work could have been done without the care and attention provided by Pangaea ship's designers and engineers from SEAMAR LLC. Developing a strong working relationship with SEAMAR as well as eventually the ship's captains and crew has been crucial to success both at the outset and as we continue to improve the instrument systems.

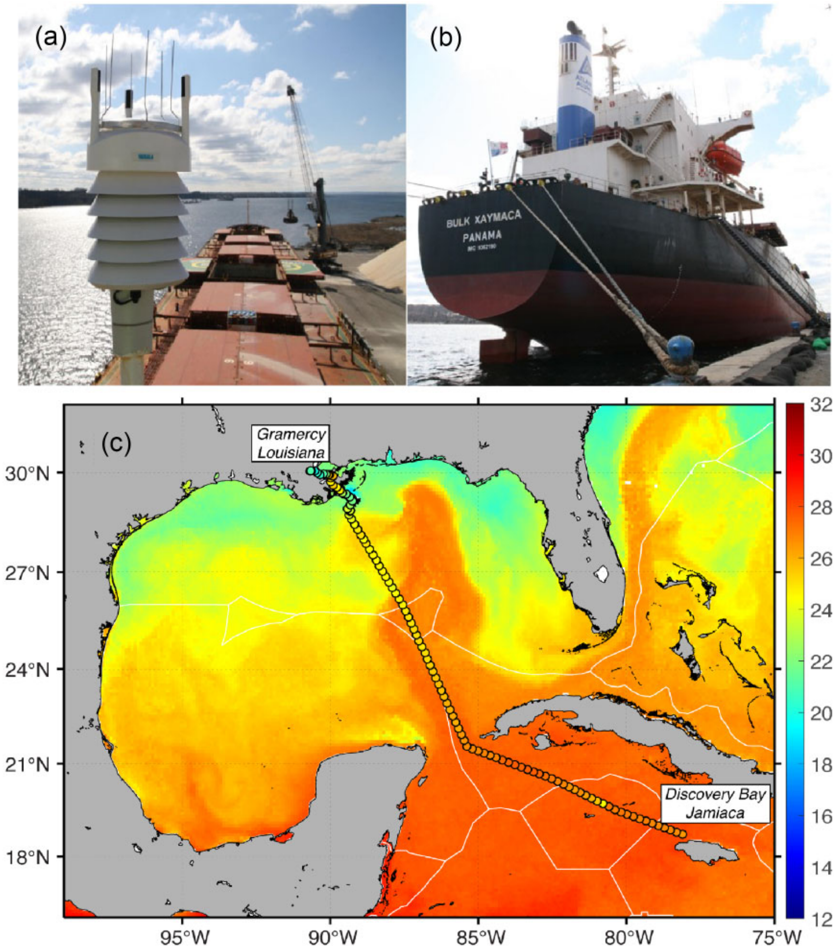

Figure 4. (a) M/V Xaymaca's Vaisala WXT-536 transmitting NRT data; (b) M/V Bulk Xaymaca; (c) CMEMS sea surface temperature (4-day average: 20–24 April 2022) in shaded contours with M/V Bulk Xaymaca's NRT *in situ* air temperature along the ship track superimposed. All temperatures in °C.

First scientific findings—Gulf of Mexico

A region of high scientific value

The GoM is a region important for the environment, climate, weather, and the economy. It sustains a wide range of ecosystems, fostering biodiversity and providing resources for local communities and the global environment (McKinney et al. 2021). Additionally, the GoM is home to one of the most energetic currents in the world. With speeds up to 2 m s^{-1} (Forristall et al. 1992, Sturges et al. 2005, Hiron et al. 2021), the Loop Current (LC), which is a part of the Atlantic western boundary current system, carries warm water from the Caribbean to the northern Atlantic (Figs 4c and 5). Consequently, alterations in the LC and heat and momentum it transports can impact the physics, chemistry, and biology of the Atlantic seaboard as well as global ocean circulation and, thereby, also the climate. Furthermore, the warm waters of the GoM can fuel hurricane intensification and impact coastal communities (Shay and Uhlhorn 2008, Shay 2010, Jaimes et al. 2016). Alongside fisheries, the GoM also hosts economically important industries such as oil and natural gas extraction, which are significantly influenced by the strong ocean currents (LC and its eddies), as well as international shipping and trade (Koch et al. 1991, Sturges et al. 2005, National Academies of Sciences, Engineering, and Medicine 2018).

The eastern GoM, through which the *Xaymaca* traverses (Fig. 4c), is highly influenced by the dynamic LC system. The pathway of the LC has three stages: (i) the retracted stage, which is the shortest path between the Yucatan and Florida Straits (Fig. 5b); (ii) the growing phase from retracted to extended (Fig. 5c); and (iii) the extended phase (Fig. 5a). When the LC reaches the last phase, it becomes baroclinically unstable and sheds an eddy, a Loop Current Eddy (LCE), which flows southwestward at ~2.5–6 cm s^{-1} (Lee and Mellor 2003, Schmitz 2005, Donohue et al. 2016, Garcia-Jove et al. 2016, Hamilton et al. 2016, Yang et al. 2020). LCE shedding is highly irregular, occurring every 6–17 months (Behringer et al. 1977, Vukovich 1988, Sturges and Leben 2000). Smaller, cold-core eddies, called Loop Current Frontal Eddies (LCFEs), propagate in the vicinity of the LC and can grow into larger eddies particularly on the northern and eastern flank of the LC, some of which participate in the LCE shedding by pinching off the LC's neck (Vukovich and Maul 1985, Lee et al. 1995, Fratantoni et al. 1998, Zavala-Hidalgo et al. 2003, Schmitz 2005, Le Hénaff et al. 2012, Hiron et al. 2020). The lifetime of large LCFEs ranges from a few weeks to a few months (Le Hénaff et al. 2014, Hiron et al. 2020, 2022).

The LC system, composed of the LC, LCE, and LCFEs, plays an important role in modulating the circulation in the eastern GoM. In addition to its role in transporting heat and salt, the LC also facilitates the transport of larvae and *Sargas-*

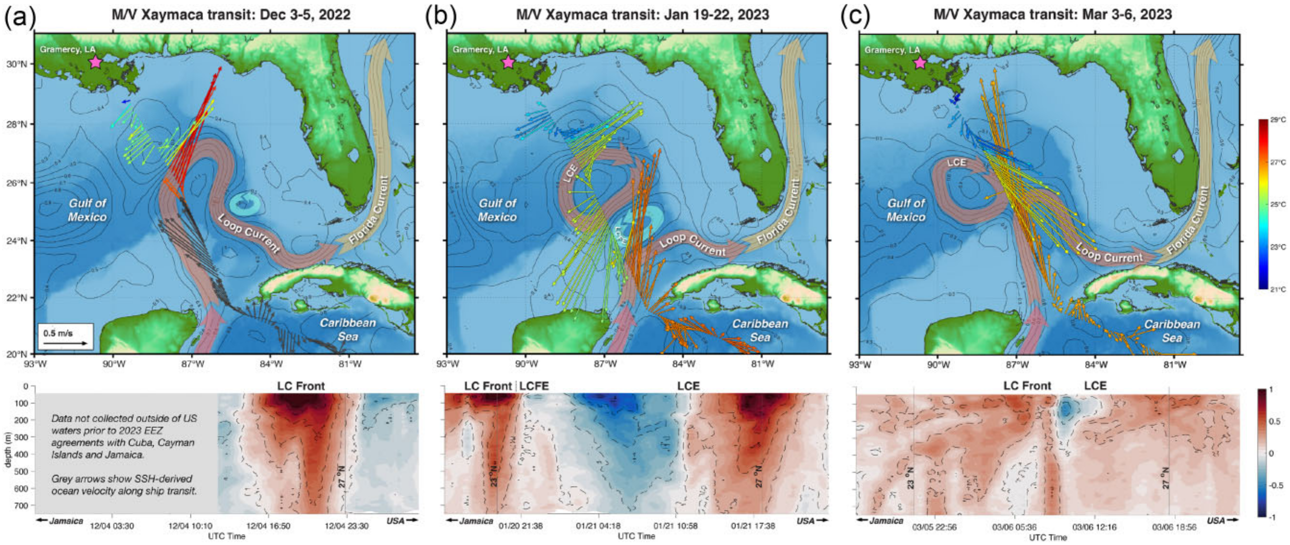

Figure 5. Shipboard ADCP engineering data measured from the M/V Bulk Xaymaca. Top: vertically averaged (45–61 m) ocean velocity (m s^{-1}, direction of arrows) and near-surface temperature (°C, color of arrows and color bar) in 40-min intervals superimposed on CMEMS Copernicus SSH (black contours, meters). Blue shading indicates bathymetry. Bottom: cross-track velocity relative to ship (m s^{-1}, blue to red colors and color bar). Positive values indicate flow toward starboard on these USA-bound transits. ADCP data collection and shipboard processing provided by UHDAS (2023). More recent ADCP velocities corrected using an inertial navigation system are considered science quality (not shown). Ship route is illustrated in Fig. 4c.

sum from the Caribbean to the Atlantic Ocean, thereby promoting connectivity between these two basins and enriching biodiversity (Tester et al. 1991, Lee and Williams 1999). The stage of the LC also affects red tide blooms on the West Florida Shelf (WFS; Olascoaga 2010, Maze et al. 2015). The Florida Red Tide, caused by the toxic dinoflagellate *Karenia brevis*, a recurring and potent harmful algae bloom, is notorious for its ability to cause extensive marine life mortality and its potential to impact human health through seafood contamination or direct contact with contaminated waters (Flewelling et al. 2005, Olascoaga 2010). Maze et al. (2015) found that periods of intense blooms on the western Florida shelf occur only when the LC is fully extended due to increase in water retention on the continental shelf. LCFEs can also affect local ecology and nearby circulation by attracting and trapping water in their interior (Olascoaga and Haller 2012, Hiron et al. 2022). An LCFE played an important role in the fate of offshore oil from the 2010 Deepwater Horizon oil spill when it trapped and maintained oil in its interior, preventing a major natural disaster in the Florida Keys predicted by the forecast models at the time (Liu et al. 2011, Walker et al. 2011, Olascoaga and Haller 2012, Hiron et al. 2022). LCFEs can also exert an influence on local biology in two ways: they can draw nutrient-rich coastal waters offshore (Hiron et al. 2022) and they can raise deep nutrient-rich waters to the surface through the upward tilting of density surfaces within cyclonic eddies (Hiron et al. 2020, Suthers et al. 2023). Both of these mechanisms have the potential to boost primary production and, in turn, enhance fish abundance.

Multiscale sampling: from large-scale to meso-scale to submesoscale motions

The *Xaymaca*'s ADCP is configured to provide two types of data: 8-m bins from ~30 to 550 m depth (broadband mode) and 16-m bins from 40 to 750 m depth (narrowband mode). Automated UHDAS (Hummon et al. 2023) processing provides 5-min averaged profiles of horizontal velocity for each ping type, which translates to one velocity profile about every 2 km. This resolution allows the ADCP to capture the large-scale LC, the mesoscale LCEs and LCFEs, and part of the submesoscale field as illustrated by the three transects that sampled the LC before, during, and after the shedding of an LCE (Fig. 5).

Strong, surface-intensified flow is observed within the LC and LCE fronts, with structure and magnitudes comparable to those reported in previous studies (Forristall et al. 1992, Sturges et al. 2005, Hiron et al. 2020). Submesoscale structures embedded within the LC near the surface and at depth are also observed in the *Xaymaca* sections (Fig. 5). The front between the LC and large LCFEs, such as the one captured on the *Xaymaca*'s track, has a meander shape and is usually highly nonlinear (Rossby number > 1; Hiron et al. 2021), which highlights the limitation of assuming that geostrophic balance holds and points to the importance of *in situ* sampling of the currents in the LC system.

More possibilities for the Gulf of Mexico route

Connecting biology and physics

There are several groups collaborating with fishing industries to improve the availability of ocean temperature data, e.g. the Moana Project (2024), which has developed an inexpensive temperature sensor designed as an attachment to commercial fishing gear (Van Vranken et al. 2023), the Gulf of Maine Lobster Foundation eMOLT Project (2024), which did the same for lobster traps (Manning and Pelletier 2009), and collaborations between the Commercial Fisheries Research Foundation (CFRF 2024) and various academic partners. Likewise, there have been efforts to collect and process acoustic data from fishing vessels (e.g. Karp 2007, Fässler et al. 2016) and in the future collaboration with these efforts could be fruitful for all parties. The unique contribution of Science RoCS would be a focus on industries with stable repeat routes.

Deploying probes from the *MV Bulk Xaymaca* to sample the subsurface temperature and salinity fields along with installation of sensors to measure underway nutrients and fluorescence would enable precise quantification of isopycnal tilting and its influence on the transport of nutrient-rich waters from the deep to the upper ocean. This allows assessment of the impact of this tilting on primary production, thereby connecting ocean physics to biological responses in the western Caribbean and GoM. A system that allows underway sampling of surface waters could also be used to measure temperature, salinity, and oxygen, as well as carbon parameters and genomics (DNA/RNA). Bioacoustics is a revolutionary field that is undergoing rapid changes but needs more observations to advance its science and technology. For example, new technology that could be utilized on these platforms includes a split beam bioacoustics transducer in conjunction with an Imaging FlowCytobot (essentially an underwater microscope) to provide a biological ground truth to accurately calculate the target strength of zooplankton species (Demer and Martin 1995). Lidar (light detection and ranging) is another sensor that could be used on commercial ships for 3D imaging. In fact, the list of possible sensors is fairly open-ended, particularly with technology that allows two-way ship/shore communication.

Model validation and forecasting

Accurate forecasting of the LC system is crucial for many applications, including prediction of oil spill transport, Florida Red Tide distributions, Sargassum transport, and hurricane intensification, as well as for other applications such as search and rescue and fisheries management. Due to its complex, nonlinear, and irregular circulation, forecasting the LC system is still a challenging task. An example would be the HYbrid Coordinate Ocean Model (HYCOM; Bleck 2002, Chassignet et al. 2003, 2006) that has been extensively employed for GoM studies and forecasting purposes (Chassignet et al. 2009, Metzger et al. 2014). One way to improve forecast models is to bring the state of the ocean model into alignment with reality through assimilation of observed data. At present, HYCOM assimilates subsurface temperature and salinity, and surface temperature and sea surface height from altimetry. The altimetry surface fields are projected into the ocean interior, which subsequently modifies the model's subsurface geostrophic velocity.

Comparing velocities from the global HYCOM data assimilative system (Metzger et al. 2014) to those observed in several of *Xaymaca*'s ADCP sections shows that there is overall agreement. A January 2023 section showing the LC during an eddy detachment and the presence of an LCFE (Fig. 6) provides illustration. Three fronts were sampled: the LC front (positive u and v ∼22.5°N), the lower flank of LCE front together with the upper flank of the LCFE front (negative u and v ∼24.5°N), and the upper flank of the LCE front (positive u and v ∼26.8°N). The cores of the fronts are found at the same location in both the model and observations (Fig. 6d–g). However, some differences are noticed in terms of velocity magnitude and vertical shear, especially in the LC front (Fig. 6b and c). Additionally, many more small structures appear in the ADCP velocities when compared to the model output.

Recent advances in modeling have enabled assimilation of surface ocean current observations from high-frequency radars, drifters, airborne measurements, etc. into high-resolution HYCOM simulations that are undergoing testing for operational use with the goal of improving LC system predictions (Eric Chassignet, pers. comm.). These surface velocity measurements are projected in the vertical by assuming an exponential decay in the upper 1000 m before assimilation. ADCP data are not currently being integrated into HYCOM, but, when available, the *Xaymaca* or other ADCP data could be directly assimilated at depth instead of using an exponential decay and ensure a better representation of the vertical shear in the upper 1000 m.

Here, for the GoM/*Xaymaca* example, we have focused on use of ocean currents in a forecast model; however, given the possible coverage (Figs 1 and 3), use of weather and ocean observations for validation or assimilation in global models, reanalyses, and even earth system models is certainly possible.

Where we go from here—seeking collaborations

Imagine the scientific advances that could be exacted were such a program in place across just one other current system or 10 or more, perhaps across the remote South Pacific, or a boundary current bordered by a country that lacks research vessels, or along a satellite track (e.g. SWOT 2023), or perhaps even across the emerging Arctic. The OceanObs19 (2019) conference provided a compelling "Vision for the Next Decade" for "Ship-Based Contributions to Global Ocean, Weather, and Climate Observing Systems" comprising five action items (Smith et al. 2019): "(1) recruiting vessels to improve both spatial and temporal sampling; (2) conducting multivariate sampling on ships; (3) raising technology readiness levels of automated shipboard sensors and ship-to-shore data communications; (4) advancing quality evaluation of observations; (5) developing a unified data management approach for observations and metadata that meet the needs of a diverse user community."

Science RoCS seeks to facilitate such an effort with the goal of transforming ocean science through industry partnerships with commercial shippers with repeat routes, creating integrated observing platforms with a global reach that will revolutionize the science community's ability to characterize variability in ocean physics, chemistry, and biology across multiple spatial and temporal scales. We are aspiring to build the portfolio of instrumentation that can be hosted on commercial vessels and are working with developers to bring emerging technology to bear, e.g. an ongoing effort to develop a detachable camera to investigate bubbles beneath moving vessels, and a novel carbon system sensor.

In summary, Science RoCS (2024) is actively seeking to build collaborations with all interested parties as we build toward our vision of globally connected stable partnerships, between ocean science and the commercial shipping industry. We are focusing our effort on three interconnected components: liaising—the continuous process of identifying and connecting all manner of users (e.g. researchers seeking to deploy instruments or use observations, students seeking training experiences, communities seeking information, and industry partners who participate with the knowledge that they are improving community safety by both informing and accessing weather forecasts improved by near-real-time observations that they themselves collect); onboard integration—a communication system to collate both near-real time and delayed-mode data from multiple sensors and allow novel measurements to be easily incorporated with minimal overhead to vessel operators; and perhaps of ultimate importance to users; post processing—timely organized post-processing of observations, including quality control, processing levels appropri-

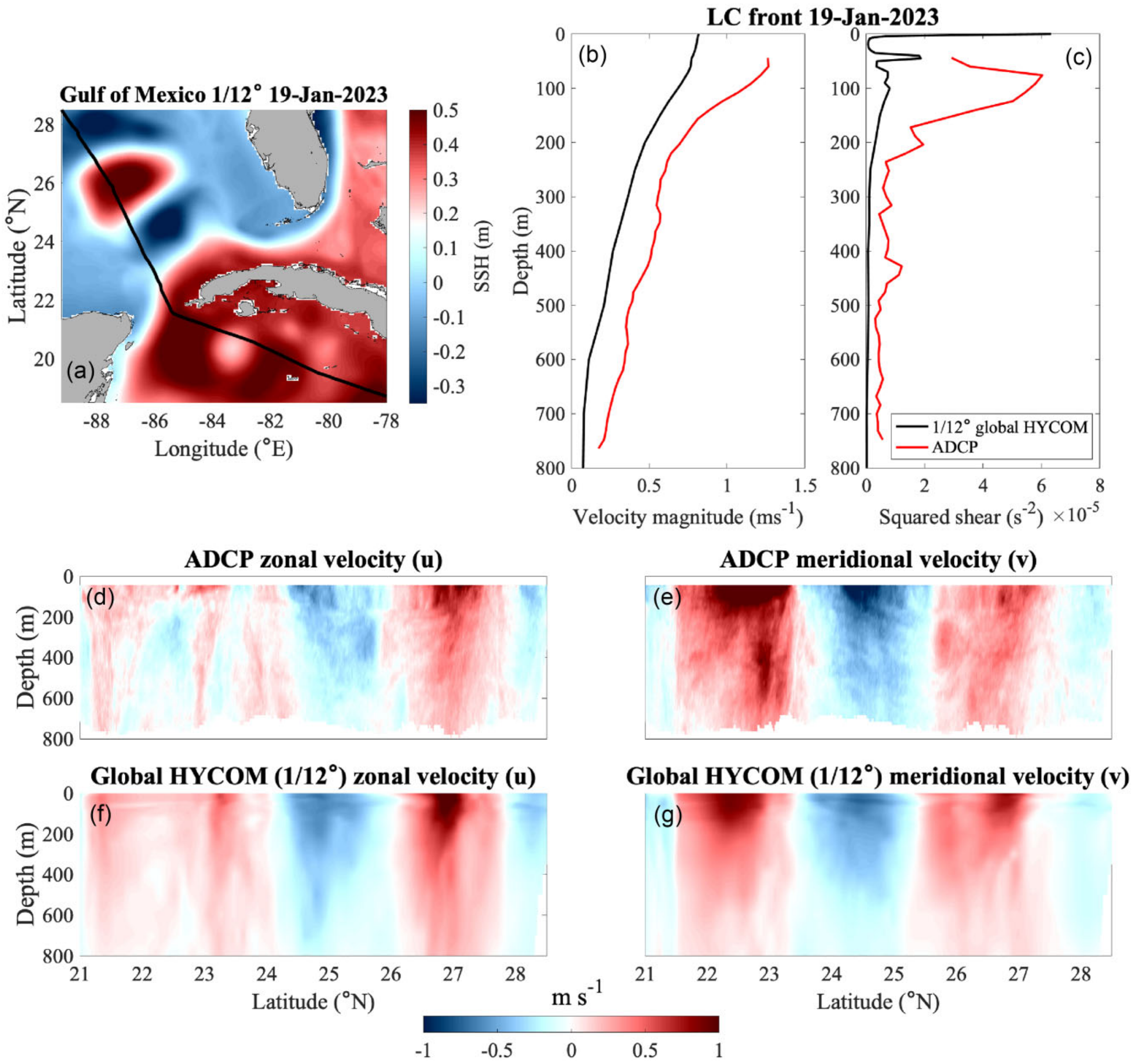

Figure 6. (a) A *Xaymaca* transect crossing the LC system on 19 January 2023 overlaid on 1/12° global HYCOM Sea Surface Height (SSH) contours (meters), with (b) velocity magnitude and (c) squared vertical shear profiles of the LC front averaged from 22°N to 23°N based on ADCP velocities (red lines) and the 1/12° global HYCOM simulation (black lines). GoM sections (zonal and meridional velocities) for (d, e) ADCP data and (f, g) 1/12° global HYCOM. The global HYCOM field was interpolated into the ADCP spatial and temporal grids to obtain equivalent spatial and temporal sampling.

ate for multiple applications, well-advertised products, and data/metadata archival—to provide observations and products suitable for a variety of stakeholders via FAIR and CARE principles (Wilkinson et al. 2016, Carroll et al. 2021).

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Author contributions

All authors contributed to conceptualization, original draft writing, review, and editing. L.M, L.H., and R.H. also contributed to the software and visualization.

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Data availability

At present, a weather station and ADCP system are installed and operational on *MV Bulk Xaymaca*. Raw and 1-min weather station data, and raw and automatically (UHDAS/CODAS, Hummon et al. 2023, doi 10.5281/zenodo.8371260) underway ADCP data are currently logged, together with GPS location/time and packaged into one data distribution per transit (defined as a transect from Louisiana to Jamaica, or vice versa). Each distribution is transferred to Woods Hole Oceanographic Institution (WHOI) using the ship's satellite internet connection and archived at Woods Hole Open Access (WHOAS 2024) within days of collection as the initial location for archival and public access (permanent link: https://hdl.handle.net/1912/67320). Each distribution has its own doi.

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