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Ocean monitoring, observation network and modelling of the Gulf of Mexico by CIGOM

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The tragic accident of the Macondo platform operated by British Petroleum (BP) unleashed in 2010 one of the largest oil spills in history, lasting over three months, spilling nearly 500 million liters of oil in one of the most biodiverse ocean regions. This accident revealed the technological deficiencies for the control of a spill in deep waters of the hydrocarbon industry. Simultaneously it showed important gaps in knowledge to predict the propagation and fate of the large volumes of hydrocarbons at depth and on the surface ocean and, more importantly, on their impact on the great ecosystem of the Gulf of Mexico. The necessity to understand and predict the transport, fate and ecosystem-level impacts of large oil spills in the southern Gulf of Mexico, a key region for oil exploration and extraction, led policymakers, scientists, and industry representatives from PEMEX (the Mexican oil company) to jointly launch an ocean observation project (2015-22) aimed to provide a multi-layered environmental baseline, develop a modern monitoring and computational modeling capacity and promote scientific understanding of the marine environment throughout the Mexican Exclusive Economic Zone (EEZ). The initiative, led by the Research Consortium for the Gulf of Mexico (CIGoM), brought together more than 300 multidisciplinary researchers from more than a two dozen institutions in Mexico and abroad, including the Centre for Scientific Research and Higher Education of Ensenada (CICESE) as the leading institution, the National Autonomous University of Mexico (UNAM), the Centre for Research and Advanced Studies of the National Polytechnic Institute (CINVESTAV) in Mérida, the Autonomous University of Baja California (UABC), and the Centre for Engineering and Industrial Development (CIDESI). Financial support was provided by the National Council for Science and Technology and the Ministry of Energy Hydrocarbon Fund.

KEYWORDS

ocean observations, environmental baseline, ocean and atmospheric modeling, Gulf of Mexico, multidisciplinary project

1 Introduction

During the last 6 years the project led by CIGoM assembled a multiplatform observation system of high-frequency radars, drifters, drones, gliders, met-ocean buoys and moorings, and satellite imagery to shed light on ocean and meteorological conditions, generating data that are fed to a web-based visualization platform. These activities were complemented by cruises that covered the deep-water region of the southern Gulf of Mexico, the Yucatan shelf, and the seagrass habitats of the Yucatan and Campeche coasts, in which regional communities were sampled and water and sediment samples were collected for integrating a wide range of physical, biogeochemical, and ecological parameters in space and time over at least 5 years. In addition, a group of modelers developed atmospheric and coupled ocean-biogeochemical models to generate oil spill scenarios for different locations in the Gulf and under different climate forcings. These oil spill scenarios were then further used in a multidisciplinary exercise to assess the vulnerability of ecosystems and key species groups in the Gulf, including large pelagic fishes, cetaceans, and marine turtles. Microbiologists used cutting-edge molecular tools to characterize microbial communities in the water column and sediments to evaluate their plastic and hydrocarbon-degrading capacities. The design of our observation platforms and monitoring efforts were initially focused on the needs of the hydrocarbon industry, such as the detection, monitoring and forecasting of dispersion and the arrival of oil following a spill, as well as their potential impact on ecosystems. However, these multiplatform observations are providing us with the necessary information to understand processes operating at timescales ranging from seasonal to interannual and from the mesoscale to large scale. All of them can help us to understand how the ocean is shifting in response to ocean warming in real time, and how they affect ecosystem structure and function. They will also provide key information on how climate warming is altering the ocean environment and its ecology and, help to assess the potential impacts on coastal communities and economic activities such as fisheries and tourism.

2 Achievements of the project

2.1 Ocean observation platforms

In the past 6 years we have implemented a system of oceanographic observations and satellite image analysis to continuously observe the surface ocean circulation, currents, marine meteorology, waves and some of the ocean essential variables like temperature, salinity, oxygen content, and chlorophyll, as well as the chemical conditions of the GoM using field measurement instruments, to establish an early warning system for hydrocarbon spill events. The system consists of a network of coastal oceanographic buoys (BOC) and open ocean oceanographic and marine meteorology buoys (BOMM), partially developed and designed at CICESE (Martínez-Osuna et al., 2021); a fleet of underwater gliders; a network of radio scatterometer stations on the coast (the only one in Latin America), and a multibeam underwater mapping system complemented on the surface by different types of satellite images ranging from passive (ocean color) to active (synthetic aperture radars). The operation of the BOC and BOMM buoy network allows for a real time transmission and continuous hydrographic, oceanographic and meteorological observations in coastal and oceanic regions of the GoM. BOCs are designed to operate in shallow waters on the continental shelf, while BOMMs are used to measure ocean and meteorological parameters in deep waters (Martínez-Osuna et al., 2021) (Figure 1).

The gliders are observation platforms designed for continuous and autonomous sampling of the water column up to 1,000 meters deep, recording various oceanographic parameters with very high spatial resolution that are sent *via* satellites back to the operations center where they are further processed. The basic instrument configuration includes sensors to measure six variables, but other instruments can be added, such as the acoustic current meters implemented in some of the CIGoM gliders. Results from these glider missions have shown the nature of intrathermocline eddies embedded within an anticyclonic eddy (Meunier et al., 2018a), to characterize the vertical structure of a large Loop Current eddy (Meunier et al., 2018b), the heat content anomaly and decay of warm core rings in the Gulf (Meunier et al., 2020). Data from different observations in the Gulf have allowed to characterize the enduring Lagrangian coherence of a Loop current ring (Beron-Vera et al, 2018b) and to elaborate a Lagrangian geography in the deep water region of Gulf of Mexico (Miron et al., 2019)

Some of these results have been used to partition the open waters of the Gulf of Mexico based on the seasonal and interannual variability of chlorophyll concentrations (Damien et al., 2018); to show how maximum concentrations of chlorophyl in winter is triggered by the deepening of the mixed layer during this season further suggesting that these maxima most likely result from a

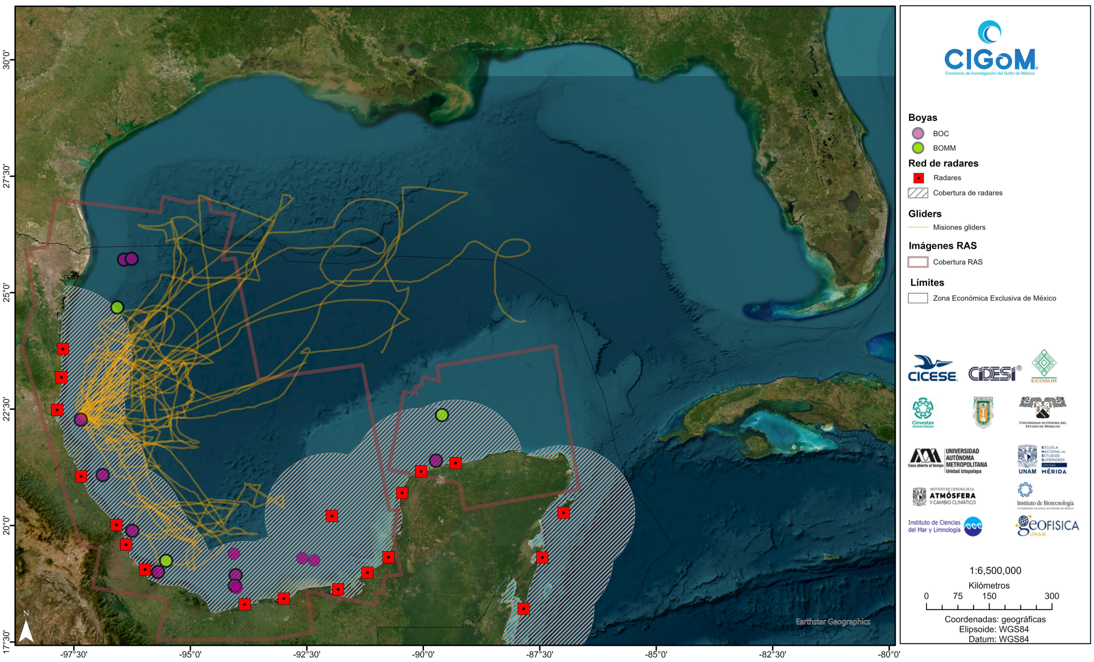


FIGURE 1
Map of the deployed observation platforms by CIGOM in the Gulf of México. Colored circles mark the buoys locations during different years (solid blue circles); location of the 19 coastal high frequency radar (HFR) stations (solid red squares) the hachured region marks the open ocean coverage of the HFR stations; yellow lines mark the trajectories of glider missions; transparent polygons mark the satellite imagery coverage.

vertical redistribution of subsurface chlorophyll and/or photo-acclimation processes, rather than a net increase of biomass (Pasqueron de Fommervault et al., 2017). Observations from ocean drifters and deep sea dispersion experiments have characterized surface and deep ocean circulation patterns in the GoM (Zavala-Sansón et al, 2017; Duran et al, 2018; Zavala-Sansón et al, 2018; Ohlmann et al, 2019; Romero et al., 2019; Lilly and Pérez-Brunius, 2021; Meunier et al, 2022). A network of deep-sea moorings deployed on the Yucatan and the Florida Straits have made important contributions to the understanding of the flow from the Caribbean through the Gulf of Mexico and into the North Atlantic Ocean (Candela et al., 2019).

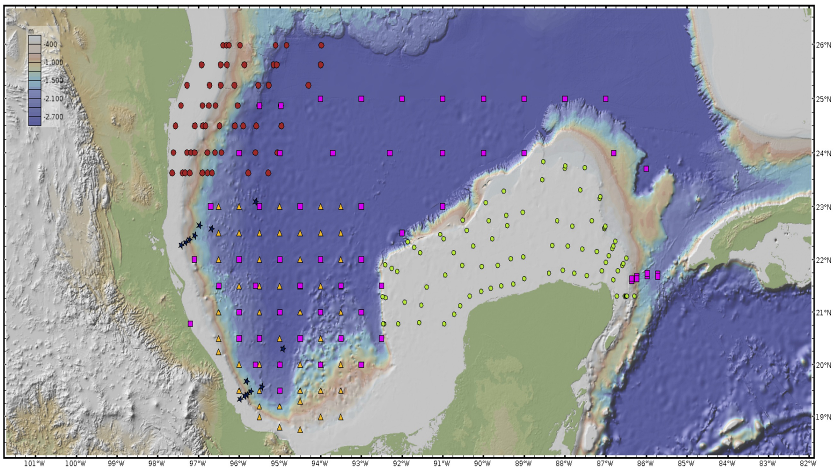
The network of radio-scatterometers or high frequency radars (HFR) is made up of a series of high-frequency Doppler radars installed around the southern GoM coast, between Tampico to the Yucatan Peninsula, providing continuous measurements of the surface currents up to 170 km offshore over the entire Exclusive Economic Zone (EEZ) (Figure 1, Map of the HFR radars cover) (Roarty et al., 2019).

The high-resolution mapping of the seabed in the Perdido region (western GoM), from the shelf brake to the abyssal plain, was made possible through multibeam system installed in the oceanographic vessel BP/Justo Sierra of UNAM. This upgraded system capable of simultaneous emission of acoustic beams and the reception of the equivalent echo, offers different capabilities ranging from high-resolution bathymetry of the seabed as well as capturing acoustic cones in the water column, that can be used to detect gas seeps at depth.

These observational systems are complemented with the analysis of active and passive satellite imagery of sea surface temperatures, and chlorophyll-a concentrations, as well as those acquired from active sensors i.e. synthetic aperture radar (SAR) images characterizing the sea surface roughness with information on waves. The CIGoM oceanographic observation system generates data to characterize ocean circulation, waves and biogeochemical processes of surface and deep waters, essential to understand the dynamics of the ecosystem, which can be further used as an indispensable tool to track the propagation and fate of oil during a spill. Additionally, the information obtained through these platforms can constitute an early warning system in case of environmental contingencies of anthropogenic origin (e.g., detection and drift of hydrocarbons) or natural (e.g., tropical cyclones), for which it is an essential component. All of them are essential tools for the establishment of national contingency plans and mitigation of impacts due to extreme events.

2.2 Atmospheric and ocean modeling

CIGoM modeling groups achieved important strides in the Mexican scientific community on the complex problems related to the prediction of the dispersion and probable fate of oil during large-scale hydrocarbon spills in the GoM, through the development of an integrated numerical modeling system. The coordinated effort of dozens of researchers from various academic institutions (CICESE and UNAM), without precedent in the



Region	Frequency	Cruises	Sampling stations
Deep waters (CICESE)	Annual	4	50
Yucatan platform (CINVESTAV)	Annual	3	87
Perdido Region (CINVESTAV)	Biannual	4	55
SW Gulf (ICML-UNAM)	Annual	4	63

FIGURE 2
Map of the cruises accomplished by CIGOM in the Gulf of México. Station visited during XIXIMI cruises in the deep water region of the GoM (filled purple squares); location of the stations visited during CINVESTAV-Mérida cruises on the Yucatán Platform (filled light green circles); location of the stations visited during the CINVESTAV-Mérida cruises in the Perdido region (filled red circles); location of the stations visited during ICML-UNAM cruises in the southern GoM (filled yellow triangles).

country's scientific community, generated its own innovative modeling system for weather and air quality forecasts, ocean circulation including waves, with the addition of biogeochemical processes, and the dispersion and fate of oil spills.

A multi-model strategy was used to simulate and reproduce the main characteristics of the GoM ocean circulation and its variability, through the implementation of eight state-of-the-art models. The advantage of this strategy consists in the robustness of the results when several model outputs coincide in their results, and when they do not coincide it can shed some light into how the differences between models are projected into the results (e.g., structures subject to greater uncertainty due to the different approaches and assumptions on which each of the models have been built models and simulations used by CIGOM can be found in the following link). https://modelacion.cigom.org/ (Jouanno et al., 2018; Gómez-Valdivia and Pares-Sierra, 2020; Maslo et al, 2020; Moreles et al., 2020).

The wave-current coupled system we developed for the GoM, consists of two models: a spectral one for waves and a hydrodynamic one for currents. The coupling allows the synchronized transfer of information between both models, so that more realistic estimates of the advection of matter (e.g. oil) can be obtained for the surface ocean Furthermore, it can be used to validate the parameterizations of the effect of waves, wind and surface ocean flow in oil spill models.

The coupling of biogeochemical modeling with the physical modeling was another achievement reached when all models used were able to successfully reproduce the distribution and concentration of chlorophyll in the water column, thus providing plausible results on the spatial and temporal characteristics of primary productivity in the GoM (Estrada-Allis et al., 2020; Guerrero et al., 2020).

A novel weather forecasting system was developed for the GoM consisting of two components. The first is used to estimate air quality and the second to calculate the evolution of polluting plumes associated with the volatilization and burning of hydrocarbons on the sea surface resulting from a large-scale spill. It should be noted that this is the only forecasting system developed in the project that can be used to reliably predict the evolution and impact of a large oil spill event on the atmosphere. https://pronosticos.atmosfera.unam.mx/atlasmeteorologico.gom/

We implemented three oil spill models of different complexity: OilSpill, PetroTrans (both 2D), and CIC-OIL (3D). These models, although based on other preexisting ones, have implemented different and innovative new routines, modifications and couplings, and stochastic theories or parameterizations that allow for the generation of new knowledge on the hydrocarbon weathering processes. In particular, the CIC-OIL model is highly sophisticated, since it couples a model to simulate the plume produced by the explosion of a well and its subsequent evolution by including several parameters, especially the nature and droplet size of the hydrocarbons which lead to

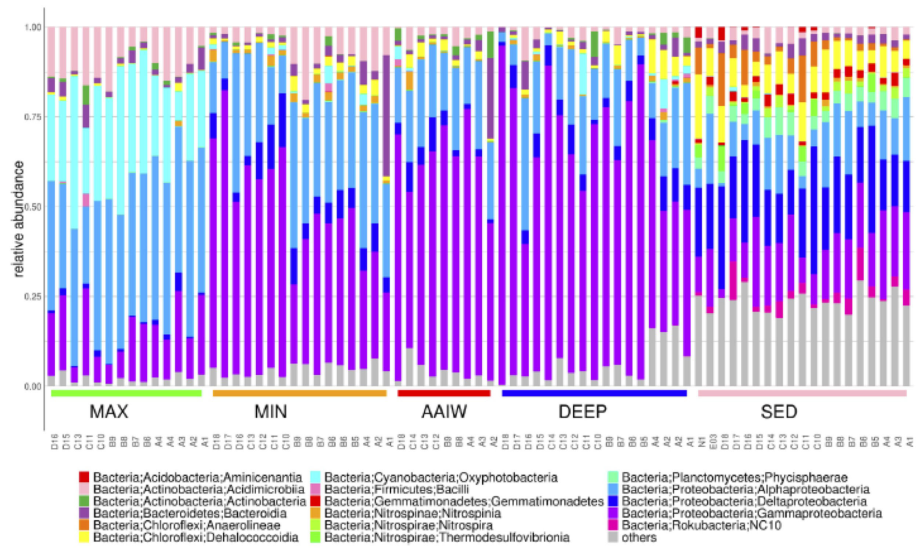


FIGURE 3
Bar plot of the relative abundances of the 16S rRNA amplicon taxonomic annotations at the Class level. Depth levels of collected samples in the water column in the central western margin (Perdido Region) and the southern GoM, maximum flurescence depth (MAX), relative oxygen minimum (MIN), Antarctic Intermediate Water mass (AAIW), waters below 1500 m depth (DEEP), sediment samples (SEDIMENT). Notice diversity changes with depth through the water column and in the sediments.

very different dispersion trajectories (Anguiano-García et al, 2019; Duteil et al., 2019; Meza-Padilla et al, 2021).

The numerical models developed by CIGoM modeling groups reproduce the main oceanographic characteristics of the GoM and its variability, providing new knowledge about the circulation and biogeochemistry of the ecosystem (Beron-Vera et al., 2018a; Beron-Vera et al., 2018b; Jouanno et al., 2018; Parés-Sierra et al, 2018; Gough et al., 2019). The meteorological forecast system, in addition to provide typical information on atmospheric circulation, essential in planning daily activities at sea (e.g., fishing, marine operations, etc.) and for the prevention, attention and mitigation of impacts and an important reanalysis effort of the last 40 years (Díaz-García et al, 2020; Allende-Arandía et al, 2022; Rodríguez-Vera et al., 2022), provides additional information on the quality of the air and the effects of gas emissions associated with hydrocarbon spills, both of great relevance for public health issues. These oil spill models provide useful results for decision makers during oil contingencies since, by providing them with information from real-time observations of marine conditions and combining them with oceanic and atmospheric forecast models. These model outputs allow for a real time forecast of the fate of a spill, as well as to generate different scenarios affecting either the different marine ecosystems as well as the health of the communities and urban population that live on the shores of the GoM, which can be used in the necessary mitigation procedures after a major oil spill.

2.3 Baseline studies and environmental variability

Generating the baseline of the GoM Large Marine Ecosystem is one of the major achievements of the project. This major milestone provides the necessary knowledge to robustly assess the impacts generated by oil spills or other natural or anthropogenic events on the Mexican EEZ waters. These baseline studies include the description of the current state and its variability of the meteorological, hydrographic, biogeochemical, biological and ecological conditions at the surface and deep waters of the GoM (Figure 2). Generating this information required an enormous multidisciplinary and inter-institutional effort that resulted in the most extensive, complete and coherent oceanographic, geochemical and ecological characterization developed in Mexico to date. Given the diversity and complexity of the ecosystem and the topics addressed, we used a wide range of scientific disciplines and applied various methodological approaches ranging from data collection (Herzka et al., 2017), analysis in the different laboratories as well as statistical and analytical procedures (HergueraDocumento en gdocs, 2017).

This baseline study was based on samples and data collected during 21 oceanographic cruises performed by five sampling programs executed by the different institutions associated with CIGoM (Table 1). One major challenge was the comparability of the results on the same variables by the different participating laboratories. One of the first actions was to standardize the procedures and protocols for on board sampling and processing of water and sediment samples, living organisms, as well as for the instrumentation and recording of oceanographic and biogeochemical variables. This standardization procedures with the participating institutions facilitated the reliability, reproducibility, validation and intercomparison of data, all of them essentially important for the development of the project (HergueraDocumento en gdocs, 2017), and especially for the future long-term monitoring of oceanographic variables and parameters of the GoM Large Marine Ecosystem.

Samples collected during these cruises and their analysis in CIGoM laboratories enabled us to establish the spatial and temporal

TABLE 1 Oceanographic cruises in the Gulf of México by CIGoM (2015-2019).

Name	Study region	Institution	Number of cruises and field operations
XIXIMI	Deep water region of the GoM	CICESE-UABC	4
GOMEX	Yucatán Platform and Yucatán channel	CINVESTAV-Mérida	3
PERDIDO	Perdido Region (W GoM)	CINVESTAV-Mérida	4
MALLA FINA/ METAGENÓMICA	Perdido Region and Coatzacoalcos	CICESE	6
SOGOM	SW deep water region	ICML-UNAM	4
Marine Seagrasses	Yucatán and Campeche shelfs	UAM-I	9

patterns of the physical and geochemical variables (Damien et al., 2018; Portela et al., 2018; Medina-Gómez et al., 2020; Ochoa et al., 2021; Cervantes-Díaz et al., 2022; Hernández-Sánchez et al, 2022; Lee-Sánchez et al., 2022; Valencia-Gasti et al, 2022; Velásquez-Aristizábal et al., 2022; Romero-Arteaga et al., 2022a; Romero-Arteaga et al., 2022b) related to the carbon cycle (as well as hydrocarbons (García-Bautista et al., 2022) metals and pollutants concentrations in the water column (Arenas-Islas et al., 2019; Hernández-Candelario et al., 2019; Árcega-Cabrera et al., 2021; Dótor-Almazán et al., 2021a; Dótor-Almazán et al., 2021b; Dótor-Almazán et al., 2021b; Árcega-Cabrera F. et al, 2022; Dótor-Almazán et al., 2022a; Dótor-Almazán et al., 2022b), sediments, as well as in tissues of selected organisms.

The development of a biological catalogue required the implementation of a wide variety of sampling and analysis techniques. Taxonomic and statistical analysis of samples collected during these oceanographic cruises allowed us to characterize the distribution and abundance patterns of phytoplankton (Linacre et al., 2019; Medina-Gómez et al., 2019; Medina-Gómez et al., 2020; Linacre et al., 2021; Améndola-Pimenta et al., 2021) fungi (Amend et al., 2019; Vargas-Gastélum et al., 2019), zooplankton (Hereu et al., 2021); ictyoplankton (Daudén-Bengoa et al., 2019; Daudén-Bengoa et al., 2020; Aguilar-Medrano et al., 2021; Compaire et al., 2021; Santana-Cisneros et al., 2021a; Santana-Cisneros et al., 2021b), demersal fish communities in the water column (Vega Cendejas et al, 2017; Vega-Cendejas and De Santillana, 2019; Aguilar-Medrano and Vega-Cendejas, 2019a; Aguilar-Medrano and Vega-Cendejas, 2019b; Aguilar-Medrano and Vega-Cendejas, 2020b; Aguilar-Medrano and Vega-Cendejas, 2020a), benthic infauna, and invertebrates in the sediments (Hernández-Avila et al., 2018; Rubio et al., 2018; Aguilar-Medrano and Vega-Cendejas, 2020b; Torruco et al., 2018; Cisterna-Céliz et al., 2019; Paz-Ríos and Pech, 2019; Hernández-Ávila et al, 2020; Martínez-Aquino et al., 2020; Paz-Ríos et al., 2020; Soler-Jimenez et al., 2021; Paz-Ríos et al., 2021; Suárez-Mozo et al., 2021; Chí-Espínola and Vega-Cendejas, 2022; Quintanar-Retama et al., 2022). Methods for taxonomic identification ranged from the use of morphological techniques to massive sequencing of DNA molecules (metagenomics) and bioinformatic data analysis (Martínez-Aquino et al, 2017; Puch-Hau et al., 2018a; Escobar-Zepeda et al., 2018; Batta-Lona et al., 2019; Tapia-Morales et al, 2019; Vargas-Gastélum et al., 2019; Sánchez-Soto et al., 2021; Aguilar- MedranoVega-Cendejas, 2021; Cicala et al., 2021; Martínez et al, 2021; Martínez et al., 2021; Santana-Cisneros et al., 2021b; Torres-Beltrán et al, 2021). Patterns of sediment composition, distribution, and sedimentation rates (Díaz-Asencio et al, 2019; Brooks et al., 2020; Diaz Asencio et al., 2020). Tissue damage and parasites distribution patterns in benthic demersal fishes (Escobedo-Hinojosa and Pardo-López, 2017; Vidal-Martínez and Wundedemersal fish communities in therlich, 2017; Puch-Hau et al., 2018b; Quintanilla-Mena et al., 2018; Vidal-Martínez et al, 2019; Quintanar-Retama et al, 2022; Cerqueda-García et al., 2020; González-Penagos et al, 2020; Rodríguez-González et al, 2020; Becerra-Amezcua et al, 2020; Cañizares-Martínez et al, 2021; Martinez et al., 2021; Ocaña et al., 2021; Vidal-Martínez et al., 2021; Zamora-Briseño et al, 2021; Ek-Huchim et al, 2022)

Satellite telemetry data on selected species generated during the project and through the implementation of ecological models using public databases and georeferenced sighting data from various sources (samples from boats and aerials, satellite telemetry) allowed us to identify critical habitats for conservation of marine vertebrates (turtles and cetaceans) and organisms of economic importance (large pelagic fishes) (Gallegos-Fernández et al., 2018; Sanvicente-Añorve et al., 2018; Cuevas et al, 2019; Cuevas et al., 2019; Lara-Hernández et al., 2019; Ocaña et al., 2019; Ramírez-León et al, 2020; García-Aguilar et al., 2021; Ramírez-León et al, 2021; Uribe-Martínez et al, 2021).

The studies developed to generate the GoM baseline, in addition to their invaluable contribution to the knowledge on the state of the GoM LME, are key elements based on scientific data that will help understand how natural resources and the economic activities that depend on them (e.g., commercial and recreational fishing, tourism, maritime traffic) could be affected by large-scale oil spills, but also by extreme events (e.g. tropical cyclones) and global warming. All this information generated is of great relevance to strengthen public policy and decision-making processes, not only within the context of the hydrocarbon industry, but also to support interventions for the conservation and responsible management of natural resources. Results from these studies are compiled in a 11 volume work that can be accessed through www.atlascigom.cicese.mx (Herzka et al., 2021).

2.4 Natural degradation of hydrocarbons

Another of the great achievements of CIGoM was the implementation and use of cutting-edge methodologies of metagenomics to characterize the hydrocarbon-degrading microbiota. The results show the extensive knowledge gathered on the diversity and abundance of bacteria in the Mexican EEZ of the GoM, from Tamaulipas to Yucatan including water and sediment collected between 550 and 3,200 meters deep, that includes bacterial consortia with metabolic capacity to degrade a variety of hydrocarbons (García-Cruz et al, 2018; Sánchez-Soto Jiménez et al, 2018; Rodríguez-Salazar et al., 2021) (Figure 3).

Samples were collected from the water column during several cruises at selected depths, i.e. maximum fluorescence, oxygen minimum, the Antarctic Intermediate Water, bottom waters and from the sediments to characterize the distribution patterns and diversity of bacterial genomes based on massive sequencing technologies such as the 16S ribosomal and shotgun. Subsequent analysis revealed the first baseline comprehensive distribution study of the bacteria that inhabit the southern Gulf of Mexico, as well as the presence of genes that code for hydrocarbon-degrading enzymes in both the Perdido region and in the Bay of Campeche, indicating an adaptation of the microbiota ecosystem to hydrocarbon environments, either from oil seeps or from oil extraction activities in the southern GoM (Gamboa-Muñoz et al, 2017; Escobar-Zepeda et al., 2018; Godoy-Lozano et al., 2018; Raggi et al., 2020).

Among the enzymes of marine origin identified and isolated are mainly hydrolases and oxidoreductases, which catalyze hydrolysis reactions of chemical bonds and oxidation-reduction reactions (Muriel-Millán et al., 2019; Moreno-Ulloa et al, 2020; Rodríguez-Salazar et al., 2020; Loza et al, 2022). In marine environments, these enzymes participate in the degradation of organic compounds, that is, they contribute to different degradation pathways of the metabolism of marine microorganisms as well as in the degradation of other toxic compounds, such as oil and plastic pollutants (Muriel-Millán et al., 2021). These enzymes are further used to process food, drugs, paper, starch, textiles and manufacture detergents by the industry.

From the perspective of the oil industry, the information can be used in an oil spill contingency to determine the presence of hydrocarbon-degrading bacteria in the affected sites and their potential for bioremediation purposes as well as biosurfactants producers. Of great interest to the hydrocarbon industry is the isolation and characterization of bacteria and bacterial consortia, as in the case of enzymes and biosurfactants discovered during the development of this research, due to their potential use in the biodegradation of contaminants (Rosas-Galván et al, 2018; Muriel-Millán et al., 2019; Curiel-Maciel et al., 2021; Morales-Guzmán et al, 2021; Rosas-Díaz et al., 2021; Rojas-Vargas et al., 2022). In addition the information on the microbiota in these environments generated can be used as indicators of the health of the oceans and can serve to guide public policy in terms of management and conservation of ecosystems. https://cruceros.cicese.mx/catalogo/

2.5 Ecological vulnerability

Quantifying and assessing the impact of an oil spill on GoM selected key species, habitats and ecoregions was another important achievement of CIGoM. This multidisciplinary work by physical oceanographers, biologists and ecologists generated large-scale oil spill scenarios in different regions, depths and climatic conditions and combined them with ecological vulnerability models and biological connectivity assessments. To achieve these results, they used a wide variety of methodological approaches at different spatial, temporal and ecological organization scales at the crossroads of different scientific disciplines https://escenarios.cigom.org/.

Results on large oil spill scenarios derived from the hydrocarbon degrading models of OilSpill, PetroTrans and CIC-OIL and atmospheric models, implemented by CIGoM, were used to determine the areas of probable impacts and the estimated times of arrival of the hydrocarbon plumes. Oceanic hydrocarbon spill models simulate the processes of transport, dispersion and weathering of oil in the sea, and atmospheric models simulate burning of oil (common practice as a measure mitigation). The procedure consisted of running hundreds of simulations of spills under similar conditions and performing a statistical ensemble of these simulations for each of the scenarios (Pérez Brunius et al., 2020b).

The identification of species and regions potentially vulnerable to oil spills was approximated through three approaches. The first consisted of evaluating the comprehensive vulnerability of sea turtles and communities of submerged aquatic vegetation, considering the multiple stressors that currently act on them. The second approach was to quantify the convergence between critical habitats of marine vertebrates (turtles, cetaceans and larger pelagic fish) and oil spill scenarios. The third one was used to determine the vulnerability of the ecosystem to oil spill scenarios considering all types of habitats that comprise up to a 100 species from different taxonomic groups (invertebrates, fish, turtles, birds and mammals) (Aguirre-Macedo et al, 2020; Liceaga-Correa et al., 2022; Romo-Curiel et al, 2022). On the other hand, the diagnosis of biological connectivity allowed the discussion on the resilience of marine populations to oil spills, with particular emphasis on the possible effects of spills in the Perdido region (Lara-Hernández et al, 2019; Sanvicente-Añorve et al., 2018; Pérez Brunius et al, 2020a; Compaire et al, 2021).

In addition to these evaluations, several experimental mesocosm protocols were implemented to determine changes in the vulnerability of phytoplankton and bacterial communities to different concentrations of oil and exposure time. These experiments were complemented with bioassays to identify indicators to evaluate vulnerability based on cellular, histological and immunological responses in two species of coastal fishes (Cañizares Martínez et al., 2018; Garcia-Cruz et al, 2019; Uribe-Flores et al, 2019; Valencia-Agami et al., 2019; Améndola-Pimenta et al, 2020; Couoh-Puga et al, 2020; González-Penagos et al, 2020; Quintanilla-Mena et al., 2020; Rodríguez-Salazar et al, 2020; Uribe-Flores et al., 2021; Zamora-Briseño et al, 2021).

Through a joint effort between researchers and decision makers, CIGOM led the planning for the attention of turtles and their habitats during an oil spill contingency http://geoportal.mda.cinvestav.mx/geoportal.html. The document produced is a national reference and guide to develop this type of planning for other protected species or species of ecological and environmental value.

All of this information generated lays the scientific foundations for strategic planning focused on the prevention, care and mitigation of oil spill incidents, while providing elements to strengthen public policies aimed at regulating the activities of the oil industry, not only in favor of the conservation of species and regions of high ecological and/or economic value, but also in favor of preserving human health in the air quality of urban areas and communities in the country.

2.6 Technological developments

Several technological advances were accomplished during the project generating observational tools to understand the complexity of processes that are triggered by a large-scale spill of hydrocarbons in the ocean.

These technological developments of the CIGoM can be divided into three large groups (Table 2):

(1) Oceanographic observation platforms. Development of five new prototypes for real-time observations of oceanographic variables and a virtual simulator. These developments were carried out by researchers from CIDESI and the UABC Institute of Oceanographic Research (IIO).

(2) Databases and visualization platforms. Development of a cyberinfrastructure with the capacity to store large databases for viewing, downloading and analysis. This cyberinfrastructure consists of six digital platforms that bring together the data, analytical approaches and model outputs carried out by researchers from all the CIGoM institutions.

(3) Bacteria consortia capable of hydrocarbon degradation. Integration of a physical reservoir and an online catalog of samples containing bacterial consortia and the metabolic pathways involved in hydrocarbon degradation. This technological development is the result of the coordinated work of researchers from IBT-UNAM, CINVESTAV Mérida-Unit, CICESE and UAEM.

3 Final remarks

The GoM is a large and complex ecosystem that harbors and supports a great biodiversity, while being one of the most important

TABLE 2 Description of the observational platforms developed by the project, technical characteristics and uses.

Observational platform	Characteristics	Utility
Unmanned aerial vehicle (UAV)	Autonomy: 1 hour Range: 40 km Cruise speed: 80 km/h Maximum speed: 120 km/h Software included (Gómez Roa et al, 2020; Orozco-Muñiz et al, 2020)	Specifically designed to liberate the microdrifters at pre designed sites The joint use of UAV y los micro drifters are a fast and cheap means of monitoring an oil spill. Especially useful during oil spills for their tracking capability of surface currents.
Marine micro drifters with control card PCB-DORIS	Equipped with GPS, sea surface temperature sensors, satellite communication and memory card Autonomy: 1 year The design allows for the coupling of different telemetry modules and up to 16 sensors	
Sampling module, includes robotic arm and removable storage tray for the ROV Lynx 1117	Design and integration of a robotic arm and one core sampling system on an observation class ROV	This system allows for the collection of samples and cores on the sea floor transforming an observational class ROV into an active sampling one
Virtual glider simulator	Captures and recreates and simulates the hydrodynamics of different gliders like Slocum and Seaglider	This simulator can be used to train glider pilots for the planning of missions (trajectories and navigation strategies under different hydrodynamic conditions) and for modeling the mechanical and hydrodynamic properties of new gliders.
Prototype glider	Weigh: 96 kg Low consumption orientation system Pitch and Roll (< 14 W) In-house designed rechargeable batteries Additional ports for more sensors. Labview operational controls and satellite communications	Shallow wáter design (< 200 m). First glider development in Mexico with a high potential on continental platform processes research
Buoy DORIS	Compact lightweight, autonomous free floating microbuoy Satellite transmission Several months autonomy	These microbuoys can be deployed from drones or adapted AUVs, very useful to track surface wáter masses and surface oil spill tracks

regions in North America in terms of energy resources. The development of this industry and its expansion into even deeper regions considerably increase the potential for oil accidents thereby increasing the risk for large-scale hydrocarbon spills, such as those occurred in 1979 and 2010 after the explosions on the platforms of the Ixtoc-I and Macondo wells, respectively.

The work developed by CIGoM responds to the need to have solid scientific information for the establishment of prevention and mitigation measures in the event of large-scale spills in the GoM, so that the country is now better prepared not only to react to an incident of this nature, but to address the challenges and needs associated with offshore hydrocarbon exploration and extraction.

The project proposed the generation of a comprehensive system of observations and numerical models to generate spill scenarios and evaluate their consequences and impacts in Mexico's EEZ of the great GoM ecosystem. The results obtained far exceeded this objective. The financing of the SENER CONACYT Hydrocarbons Fund for the development of the project allowed us to characterize the current state of the physical, chemical and biotic environment of the GoM based on real-time and continuous observations from different oceanographic observation platforms, has deepen our knowledge of ocean and atmospheric circulation, the biogeochemical and ecological processes in the water column and in the sediments, the characterization of the hydrocarbon-degrading microbiota, and the elaboration of vulnerability scenarios for key ecosystems and species. In addition, the capacity of hundreds of researchers, technicians, postdoctoral students and students was strengthened, as well as the scientific and technological infrastructure of national academic institutions, which gave rise to the generation of the largest existing scientific heritage in the Mexican EEZ waters of the GoM.

Achieving these goals in the past seven years was possible thanks to the commitment of the participating researchers, students' postdocs and technicians, as well as the professional monitoring and management team of the project that allowed for inter-institutional liaison, linkage and communication, constant evaluation of the progress, identified and anticipated the risks and made it possible to reach the objectives and committed to results.

The multi-institutional and interdisciplinary work financed by the SENER-CONACYT Hydrocarbons Fund brought together the work of more than 300 researchers from 17 national and international institutions in a coordinated manner and with a common goal, to generate the necessary information to support decision-making, informed and rational planning and mitigation strategies in the event of a large-scale oil spill with potentially devastating effects on human communities in the coastal zone, fishery production and ecosystem health. Additionally, the knowledge and skills developed strengthen public policies oriented towards the conservation and sustainable management of the GoM's natural resources and the ecosystem services it provides.

CIGoM achievements to address research and management issues related to the hydrocarbon industry are unprecedented in Mexico. However, given the dynamic nature of the great ecosystem of the GoM, the trends induced by global climate warming, and the continuous development and expansion of oil exploration and extraction activities towards deep waters, it is essential to continue growing and nurturing the human and infrastructure capacities generated during the project to meet the future needs of industry and society.

4 Nomenclature

4.1 Resource identification initiative

To take part in the Resource Identification Initiative, please use the corresponding catalog number and RRID in your current manuscript. For more information about the project and for steps on how to search for an RRID, please click here.

4.2 Life Science identifiers

Life Science Identifiers (LSIDs) for ZOOBANK registered names or nomenclatural acts should be listed in the manuscript before the keywords with the following format:

urn:lsid:<Authority>:<Namespace>:<ObjectID>[:<Version>]

For more information on LSIDs please see Inclusion of Zoological Nomenclature section of the guidelines.

4.3 Additional requirements

For additional requirements for specific article types and further information please refer to Author Guidelines.

Author contributions

JH wrote the article and all of the authors contributed to the review process. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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