Current Tides

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A Letter From the Chair

I am pleased, impressed, and honoured to write my second opening to *Current Tides* during my term as Chair of the Department of Oceanography. This remarkable initiative was conceived of and is produced by our graduate students. Bringing each edition to press takes a combination of passion and patience; ambition and attention; humour and hard work. The two previous editions of Current Tides set a high standard for scholarship and production values, and this third edition rises to the same heights.

Current Tides beautifully documents the ongoing and deep commitment to interdisciplinary ocean science that has motivated the Department since its inception. In this issue, our students present research that spans the living world from bacteria to whales and the geographic world from the continents to the deep sea. Anne dives right into the fascinating science of the underwater soundscape, which is so important to communication, prey detection, and predator avoidance in the ocean. Kevin introduces us to the complexities of predator-prey interactions between small organisms, followed by Jonathan, who describes his research into the importance of rivers for delivery of life-sustaining nutrients to our productive coastal waters. Alysse takes a different tack by exploring how the copious sediments delivered to the ocean during flash floods, under certain circumstances, can be used to reconstruct past episodes of flooding on land. Microbes are next. Sebastian explains how sophisticated measurements of nitrogen isotopes and analysis of DNA are being used to unravel how these tiny but incredibly abundant organisms regulate Earth's nitrogen cycles, with emphasis on how low oxygen levels affect the rates and pathways of nitrogen cycling. Liuqian describes how powerful computer models today are blended elegantly with increasingly sophisticated ocean observations to help us to predict the consequences of human activities on the marine ecosystems of the Gulf of Mexico. Francisco's research centres on coastal sediments, which in many ways serve the same purpose as compost piles on land, breaking down dead and decaying material so it can support future productivity. Jacoba takes us north to the Arctic, where she participated in a multi-year effort to improve understanding of the fate of atmospheric carbon dioxide as it interacts with the ocean at the top of our planet. Finally, Danielle guides us through the very timely science of food supply and acquisition for endangered North Atlantic Right Whales in Nova Scotian waters.

Hats off to Editor-in-Chief Lorenza Raimondi, as well as to the editorial staff and the print and graphic designers, for producing this edition of *Current Tides*. Your efforts will help to spread the word about the wonder and importance of ocean discovery. Bravo Zulu!

Paul Hill
Chair of the Department of Oceanography

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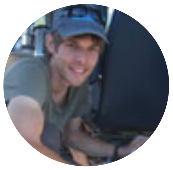
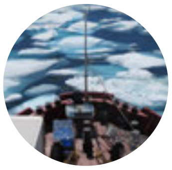




From Dead Zones to Oil Spills

Understanding human impacts in the Gulf of Mexico with numerical models and data assimilation

Liuqian Yu

Human impacts in Gulf of Mexico

It might be hard to imagine, but a drop of water from the small glacial lake known as Lake Itasca in Minnesota flows 2340 miles (3770 kilometres) southwards to the Gulf of Mexico (GOM). The lake water, together with many other sources, constitutes the Mississippi River, which is the chief river of the largest drainage system in North America, covering 41% of the contiguous United States (Figure 1). The freshwater discharge from the river forms a fresher and therefore lighter layer on top of the saltier and heavier seawater in the northern GOM (Figure 2). In summer, the sunlight continuously heats the surface layer, enhancing the density differences between the surface and deeper water layers, thereby strengthening vertical stratification of the water column. The strong stratification limits the oxygen exchange between oxygen-rich surface and oxygen-poor bottom water. Additionally, extremely high loads of nutrients (for example, nitrate and phosphate) carried by the Mississippi River, mostly from farm runoff and animal waste, are released into the gulf water, stimulating large algae blooms in the northern GOM. When these algae die, they sink to the bottom where they are decomposed by bacteria that simultaneously consume oxygen. Here, where oxygen supply from above is already limited, the continuous consumption of oxygen generates a hypoxic (low-oxygen) dead zone in the northern GOM (Figure 1) that impacts the normal function of living organisms.

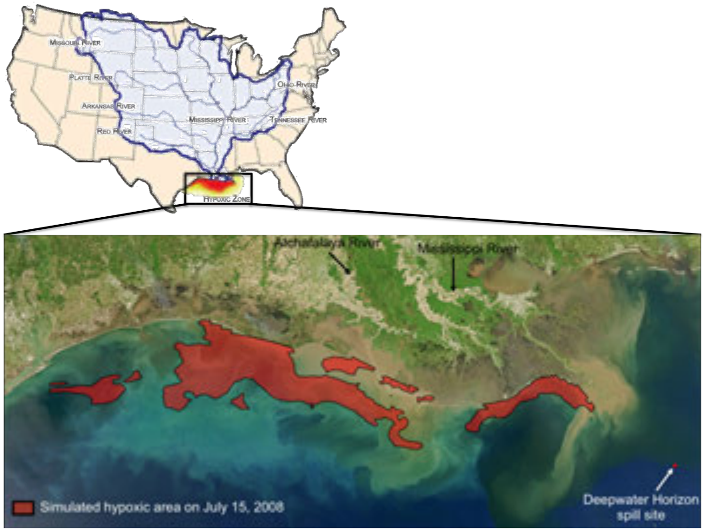


Figure1. *Satellite image (MODIS sensor) showing the plumes from the Mississippi and Atchafalaya Rivers. Red area represents approximate size and location of hypoxic zone from model simulation. Left upper corner: A map of the Mississippi River drainage basin (light purple block, picture from US EPA). Source Data Credit: NASA, US EPA, Arnaud Laurent.*

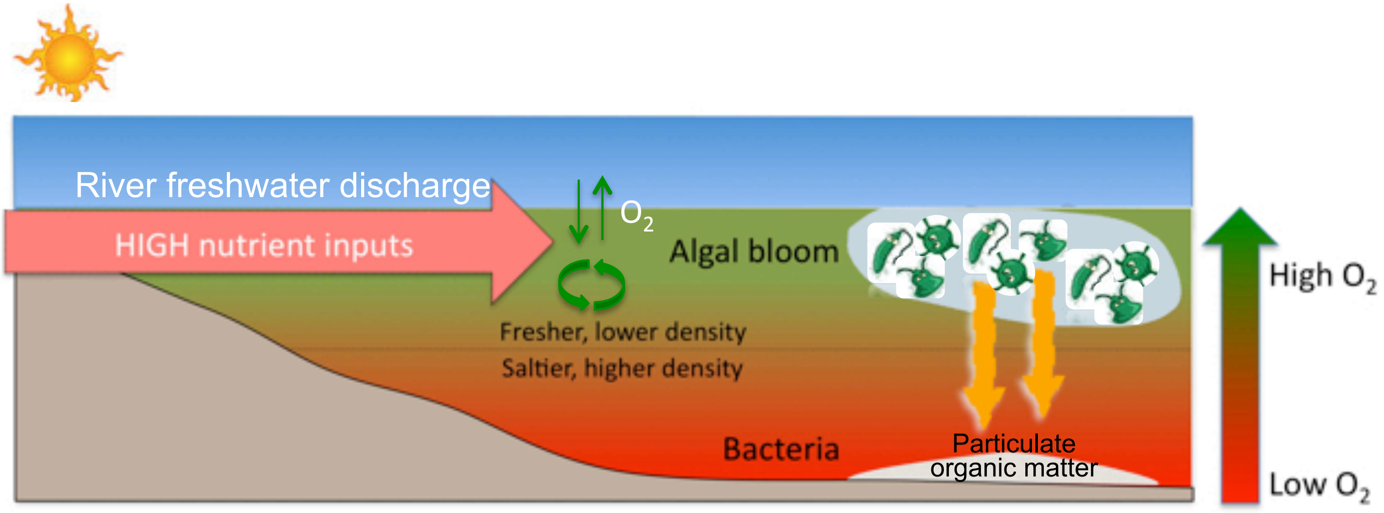


Figure 2. *Schematic of low-oxygen dead zone formation (adapted from http://www.vims.edu/).*

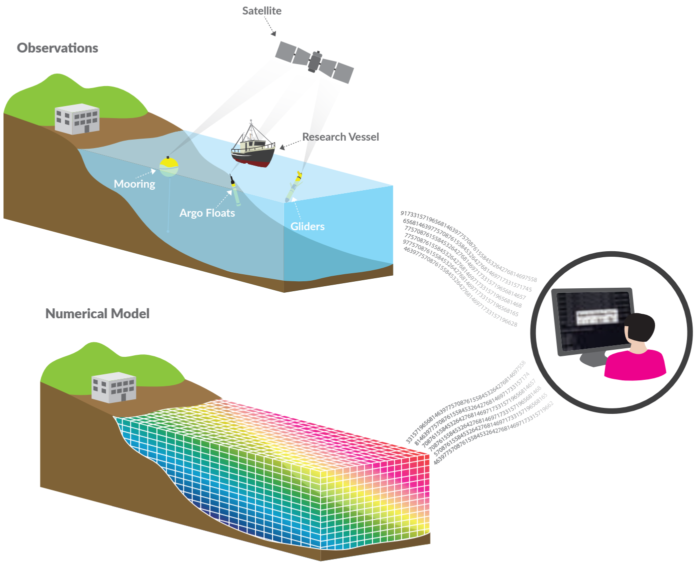
Further off the coast, the deeper waters in the GOM may be less impacted by the farm runoff, but are increasingly stressed by the intensive oil and gas exploration in the deep GOM. Most recently, the explosion and sinking of the offshore drilling rig Deepwater Horizon in the GOM in April 2010 created the worst oil spill in U.S. history. During the event, an unprecedented 4.9 million barrels of crude oil was released into the GOM at an approximate water depth of 1500 metres. It is estimated that more than half of the leaking mixtures rose to the sea surface. Conversely, the neutrally buoyant fraction of the oil, meaning it had the same density as the surrounding seawater, formed hydrocarbon-enriched plumes at depths between 1000 and 1200 metres. These deep plumes are estimated to have made up to about 36% of the leaking mixture by mass, and comprise both water-soluble hydrocarbons and suspended trapped oil droplets. While much of the water-soluble hydrocarbons are observed to undergo rapid biodegradation that simultaneously consume oxygen, the fate of the suspended hydrocarbons and their impacts on the deep sea ecology remain uncertain.

Efforts are underway to reduce the nutrient inputs into the GOM in order to reduce the extent and severity of hypoxic conditions in the coastal region here. To evaluate the effectiveness of these nutrient management strategies, it is essential to quantify the importance of different processes (such as water column stratification and nutrient-enhanced production) in regulating hypoxia development in the northern GOM. Quantifying these processes is not trivial since they interact in non-linear ways and may vary in time and space. Similarly, many efforts have been taken to track the hydrocarbon plumes following the Deepwater Horizon oil spill in order to understand and alleviate their negative impacts. Nevertheless, we still have limited understanding of where deep-water hydrocarbon plumes are distributed, how far they spread, and how fast they degrade. To answer these questions and improve our understanding of human impacts in the GOM, one invaluable tool is combining the information from numerical models and observations.

Combining numerical models and observations

Numerical ocean models are tools that simulate ocean conditions by solving complex mathematical equations with numerical time-stepping procedures. They have been widely applied in marine systems to advance our understanding of ocean processes, and provide useful information for marine management and decision-making.

However, as the great statistician George E.P. Box stated, ‘essentially, all models are wrong, …’. The models he referred to are any simplification or approximation of reality that we construct to understand real world systems. Indeed, numerical ocean models are by definition mere representations of the ocean ecosystems. Models tend to only involve a limited number of complex processes that are represented as simplified characterizations; errors that are associated with such approximations and assumptions are therefore inherent in models.



Data assimilation bridges numerical models and observations.

Nevertheless, ‘… some models are useful’, as the second half of the quote by Box goes. To make the models ‘useful’, observations are often applied for validating and calibrating models and provide an important source of information for understanding the ocean. Past decades have witnessed a revolution in global ocean-observing capabilities, providing an unprecedented view of marine systems from the ocean surface to the ocean interior. Of course, these observations also contain errors arising from the way we obtain them (for example, error in the sampling procedures, sensor and instrumental uncertainty). Moreover, despite substantially improved data coverage, the ocean is still undersampled with respect to its temporal and spatial scales of variability and complexity.

In all, models and observations individually are insufficient to provide accurate representations of the ocean state; combining them is crucial to improve our understanding of the ocean system. Methods that combine the information in observations and dynamical models provide more accurate estimates of the true ocean state and its parameters, and are called data assimilation techniques. One widely applied assimilation method is the Ensemble Kalman Filter (EnKF) (Figure 3). The idea is to use an ensemble of model simulations to approximate model uncertainty and update the model state by utilizing available observations as the model ensemble is integrated forward in time. It consists of two steps: forecast and analysis. During the forecast step, the model state variables are integrated forward in time with an ensemble of model simulations. During the analysis step, the model outputs and observations are optimally blended according to their respective uncertainties. More specifically,

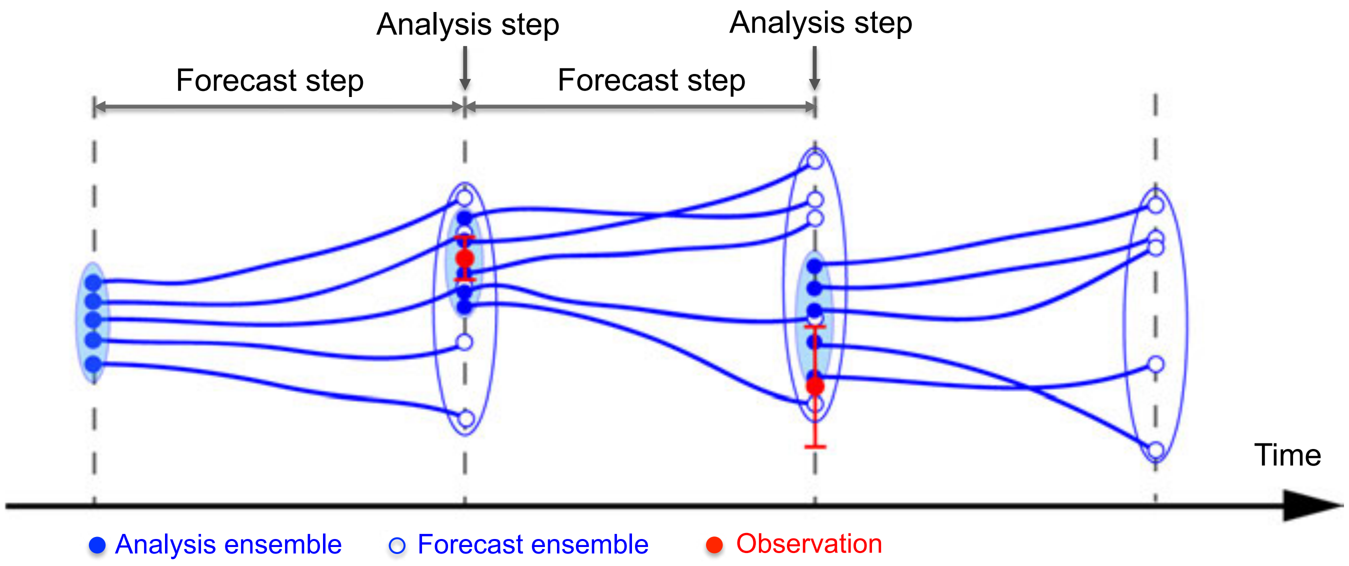


Figure 3. *Schematic diagram of the Ensemble Kalman Filter procedure. During the forecast step, an ensemble of model simulations (blue) is integrated forward in time until observations are available. The forecast ensemble (empty dots) provides an estimate of the model uncertainty (represented by the empty ellipse), which is used in the analysis step (Kalman Filter update step) to provide a new analysis ensemble (filled dots) with reduced uncertainty (represented by the light blue ellipse). The more accurate the observation is (smaller observation error bar) relative to the model uncertainty, the stronger the update strength is, and the closer the analysis ensemble is drawn to the observation.*

the more accurate the observation is, the closer the analysis will be drawn to the observation.

By applying numerical models and data assimilation methods, we aim to improve our understanding and prediction capability of the processes associated with hypoxia and oil spills in the GOM.

Applying Our Methods

I. Primary processes controlling hypoxia (a.k.a. the dead zone)

Understanding the occurrence of hypoxia and designing effective nutrient management strategy in the northern GOM requires quantitative knowledge of the processes controlling dissolved oxygen concentrations and how they vary in time and space. These include physical processes (such as air-sea exchange of oxygen, and the transport and mixing of oxygen in the water column) and biogeochemical processes (such as photosynthetic production, water column respiration and nitrification, and oxygen consumption in the sediments). To explicitly simulate oxygen and its controlling processes, we implement a three-dimensional coupled physical-biogeochemical model. The physical model is configured by the Regional Ocean Modelling System (ROMS) for the Mississippi/Atchafalaya outflow region, which simulates the physical processes controlling air-sea exchange, transport and mixing of oxygen. The biological model simulates the nitrogen and phosphorus cycles that involve oxygen production and consumption processes.

We first conduct model-data comparisons to evaluate how well the model simulates oxygen and its controlling processes (in modelling we call this a “model validation”), and then make adjustments to the model to achieve better agreement with observations. The validated model is then used to calculate the oxygen budget for different regions and different vertical depths to quantify the relative importance of the controlling processes and examine how they vary in space.

Through the budget analyses, we found that the combination of physical processes and sediment oxygen consumption are responsible for most of the spatial and temporal variability of hypoxia in the northern GOM. This finding highlights the importance of quantifying physical processes in regulating hypoxia when designing effective and sound nutrient reduction plan, as the physical processes will confound the response of hypoxia to river nutrient load reductions.

To better understand the relative importance of the physical factors, such as wind speed and direction, and river discharge on hypoxia, we use the same physical model described above but couple it to a simple oxygen model to examine the physical controls on hypoxia generation in the northern GOM. The simple oxygen model describes biological oxygen production and consumption terms using relationships derived from observations. Namely, the model assumes a constant oxygen utilization rate (the sum of production and consumption of oxygen) in the water column, and an oxygen- and temperature-dependent oxygen consumption rate in the sediment. Despite its simplicity, we found that the model can reproduce the observed variability of dissolved oxygen and hypoxia in the northern GOM. As the model is independent of nutrient loads, it allows us to investigate the impacts of physical factors on hypoxia generation without the potential confounding effects of a full biogeochemical model like we used for calculating the oxygen budget.

II. Tracking the deep-water hydrocarbon plumes

In the event of a deep-water oil spill like the 2010 Deepwater Horizon disaster, the ability to predict the movement and decay of hydrocarbon plumes in the water column becomes very important. To do so requires numerical models that best simulate the physical and biogeochemical processes regulating hydrocarbon transport and decay. To that aim, we develop a coupled physical-hydrocarbon model. The physical model is configured for the whole Gulf of Mexico to simulate the transport and mixing of hydrocarbon and oxygen, and the hydrocarbon model simulates the hydrocarbon decay in the water column that consumes oxygen. The EnKF method is implemented into the model to more accurately track the hydrocarbon transport. Specifically, we generate an ensemble of artificial wind forcing files and hydrocarbon decay rates to create an ensemble of model simulations. By using a mean value from the ensemble simulations we obtain estimates of ocean fields such as the temperature, salinity, sea surface height, hydrocarbon and oxygen, as well as the uncertainty of these estimated fields (represented by the ensemble spread). Once observations are available at a time step, such as satellite observations of sea surface temperature (SST) and sea surface height (SSH), and depth profiles of temperature, salinity and oxygen, the ensemble model simulations stop and correct the simulated fields to reduce the model-data difference. This process is called an analysis or assimilation step as shown in Figure 3, after which the ensemble model restarts from the updated state and run until observations are available at the next time. We found that assimilating satellite-derived surface data (SST and SSH) significantly improves model simulated fields and predictive skill. The improvement is largely attributed to the assimilation of SSH data, due to its tight correlation with interior temperature and salinity fields. When assimilating temperature and salinity along the water column in addition to surface data, model simulated subsurface fields and predictive skill are further improved, demonstrating the importance of collecting and utilizing depth profiles of ocean fields. The fact that we have been able to improve our model simulated subsurface fields is encouraging since their accurate representation is essential for understanding and predicting the movement of deep-water hydrocarbons. Ultimately the data-assimilative model developed here will be part of a rapid response capability that can be deployed in the event of an oil spill to improve mitigation approaches by emergency responders and policy makers.

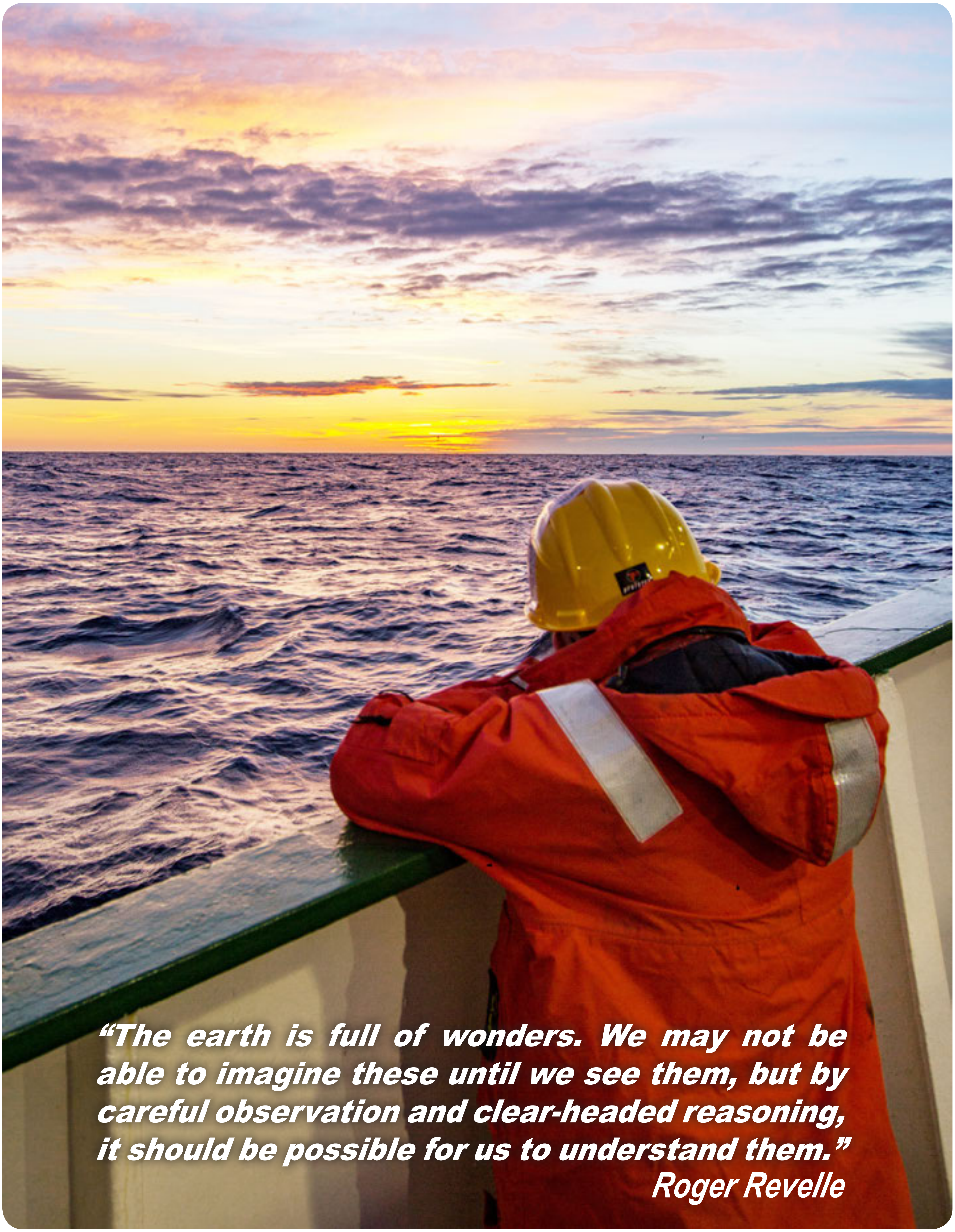
A Tale of Two Oceans

In short, it was the worst of times for ocean systems like the Gulf of Mexico that are increasingly stressed by human-induced changes. However, it was also the best of times for ocean research. The unprecedented amount and quality of observational data, and the rapidly growing capabilities of numerical models are a winning combination that helps us better understand, predict and protect the ocean in the changing times.

THIS RESEARCH WAS FUNDED BY THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION'S (NOAA) CENTERS FOR SPONSORED COASTAL OCEAN RESEARCH (CSCOR) GRANT, THE U.S. INTEGRATED OCEAN OBSERVING SYSTEM (IOOS) COASTAL OCEAN MODELLING TESTBED, THE GRANT FROM GULF OF MEXICO RESEARCH INITIATIVE (GOMRI), NOVA SCOTIA GRADUATE SCHOLARSHIP, AND PREDICTION AND OBSERVATION OF THE MARINE ENVIRONMENT (POME) NORWEGIAN-CANADIAN EXCHANGE PROGRAMME.

Liuqian Yu

Growing up in a mountainous region of southern China, studying the ocean was not among the many childhood dreams of Liuqian. But she got fascinated by the ocean immediately at her first visit, for its breadth, endless variety, and beautiful seashells that she so loved collecting. Having a strong interest in science and a love and concern for the environment, Liuqian pursued a Bachelor's degree in environmental science at Sun Yat-sen University. After graduation, she worked in a provincial lab focusing on soil greenhouse gas emission. In 2012, needing more of a challenge, Liuqian came to Nova Scotia to pursue a PhD in biological oceanography at Dalhousie University with Dr. Katja Fennel. When not working, Liuqian loves spending time with her husband, Nanju, reading books, baking, running, and hiking.



“The earth is full of wonders. We may not be able to imagine these until we see them, but by careful observation and clear-headed reasoning, it should be possible for us to understand them.”

Roger Revelle

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