Current Tides

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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

Contents

Let the Bay Have its Say

A harmonious perspective on underwater sounds at a planned in-stream tidal energy site

Anne Lombardi

Waves crashing on shorelines, raindrops pattering on calm waters, the hum of an outboard motor – even if you've never heard the term "soundscape", you have certainly *heard* a marine soundscape. Like the dynamic compilation of sounds contributing to the above-sea acoustic environment – think leaves blowing in trees, planes passing overhead, barking dogs and chirping birds – there exists as well a diverse and dynamic symphony below the ocean surface. The various contributors to this compilation are often categorized based on sounds from human activity (anthropophony), sounds from marine life (biophony), and sounds from the physical environment (geophony).

Given the importance of sound for communication, feeding and spatial awareness for marine life forms, the underwater soundscape is a crucial component of marine ecosystems. The soundscape, however, is by no means exempt from disruption from human activity, and our understanding of anthropogenic acoustic impacts on marine life is incomplete. This knowledge gap is particularly evident in the context of tidal energy development in the Bay of Fundy. The question of natural soundscape versus tidal turbine infrastructure was the bait leading this environmental engineer out of the urban landscape and into the turbulent waters of Grand Passage, Nova Scotia.

Grand schemes for Grand Passage sounds

Grand Passage is a narrow, shallow channel separating Long Island and Brier Island in the Bay of Fundy, where the high energy tides generate flow speeds over 2.5 metres per second (m/s) or 9 kilometres per hour (km/hr; for reference, a jogging pace). Due to the strong currents, the Passage has been selected as a development site for in-stream tidal energy generation. The region hosts a diverse marine life population, which is thoroughly integrated into existing human marine activities; large populations of fishes support a long-standing local fishery, and several species of marine mammals (including the endangered North Atlantic right whale) draw packs of tourists for whale-watching. In addition, a local diesel-electric ferry crosses the passage twice per hour to transport people and goods between the islands. This active environment generates a diverse range of sounds, yielding a soundscape that is "noisy" compared

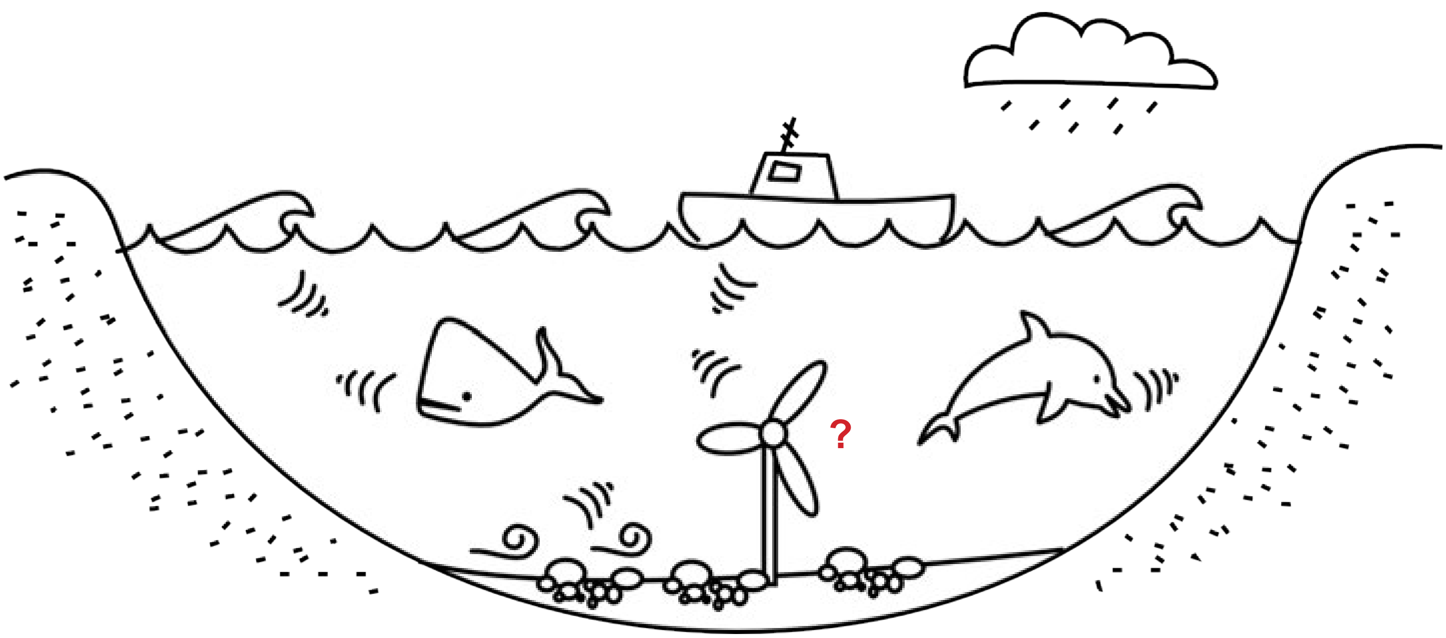


Figure 1. *Conceptual representation of the Grand Passage soundscape following installation of tidal turbine infrastructure*

to an open ocean environment. An important question becomes: If one or more tidal turbines are added to this mix (Figure 1), how might the soundscape change, and how might the ecosystem respond?

Using a collection of stationary and drifting hydrophones for passive acoustic data collection (essentially underwater microphones recording sound files), combined with concurrent records of flow speeds and meteorological conditions, the present research examines the existing soundscape conditions to provide a foundation for improved monitoring and assessment of underwater sounds following turbine deployment. The research seeks to characterize the Grand Passage soundscape prior to turbine installation, with a focus on the geophonic contribution, as the sounds of physical origin (wave action and seabed sediment motion) are often the loudest natural sources in shallow, high-flow environments. Sounds are classified based on their origin, which enables a more direct comparison with present and future soundscape research results. In addition, a categorical approach enables a more detailed evaluation of specific sound sources in different time and space conditions.

Shallow waters, deep complexity: How to measure all the sounds while not measuring non-sounds

Sound waves in the ocean travel along defined paths, and the path directions are governed by the water properties (temperature, salinity), surface conditions (waves), and bottom/coast geology and topography (rock type and seabed shape). When a sound wave interacts with any change in physical conditions – for example, when sound hits the water surface or seabed, or passes through a warmer or colder layer – the path direction changes and the sound level (signal amplitude) can be decreased. In the open ocean, where water depths are on the order of kilometres, sound transmission is less interrupted and sound levels remain relatively constant over small distances. Shallow channel environments, by contrast, exhibit significant spatial variability, as the sounds are reflected from the seabed and surface boundaries, losing energy and changing direction with each interaction. With depths between approximately 10-30 metres and a maximum width of 1 kilometre, the Grand Passage soundscape is heavily influenced by channel geometry. The result is that a hydrophone receiver located on the bottom in the center of Grand Passage will “hear” a much different soundscape than a receiver located near the shoreline or near the channel entrance.

In coastal environments, sound levels can be highly variable in time as well as in space. The high energy flows passing over a sand-gravel seabed results in the mobilization of large volumes of sediment, which generates significant noise as rocks and sand grains collide. These tidal flows exhibit varying speeds on diurnal (flood/ebb variability), biweekly (spring/neap variability), and monthly (apogee/perigee) time scales, which results in time-varying sound levels generated from sediment movement. Thus, a hydrophone located on the bottom will hear a much different record at different times of the day and different days of the year.

High flow environments also present technological challenges for the collection of passive acoustic data. Sounds are measured by recording pressure changes at the hydrophone, where a louder sound would generate a higher pressure. The strong currents in Grand Passage have high levels of turbulence, and variable pressures exist within turbulent eddies that can act as “fake” sounds: As turbulent currents pass over the receiver, the eddies generate pressure signals at the hydrophone that are not true acoustic sources. These non-acoustic signals, which occur in land-based microphones as well, were a subject of much investigation by several physicists beginning the mid-1900s and were labelled “pseudonoise” by Murray Lighthill in 1962. As pseudonoise is caused by the relative motion between the receiver and the flow, the effects can be reduced by minimizing the relative motion; in practice, minimizing relative motion means deploying hydrophones in a low flow location or allowing the equipment to move with the current. In addition, the properties of pseudonoise are unique to any given receiver and can be identified through evaluation of the signal coherence (similarity of sounds) between multiple hydrophones separated by a small distance.

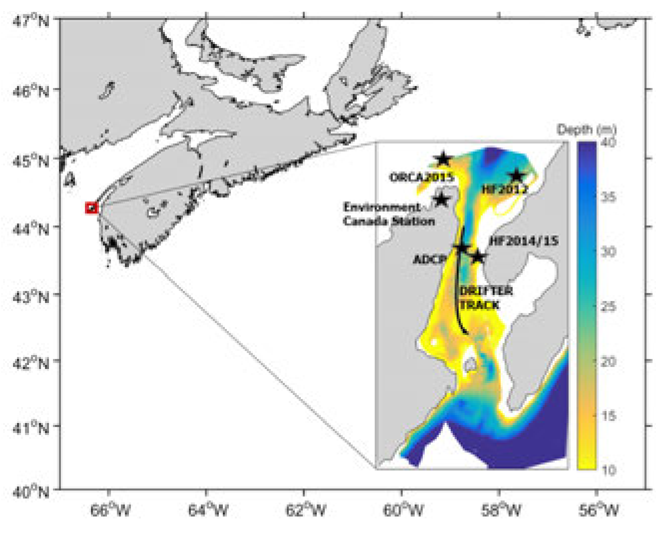


Figure 2. Grand Passage bathymetry and instrument locations.

As part of a 2012 study on hydrophone flow shields conducted by Dalhousie’s Ocean Acoustics Lab, passive acoustic datasets were collected using a single-channel (one receiver) drifting hydrophone as well as a moored (anchored to bottom) hydrophone at the northern channel entrance. The techniques and findings of that study provided a foundation for the development of a combined drifting/moored approach used in the present research. To minimize and identify pseudonoise effects, and to capture temporal and spatial

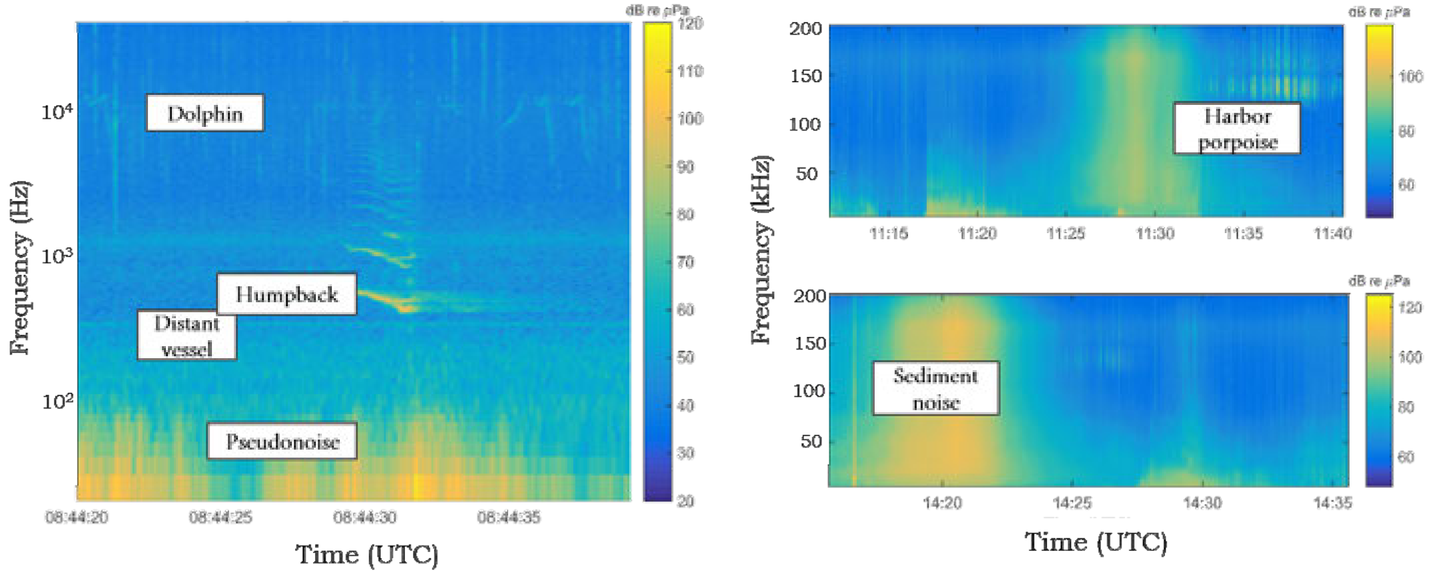


Figure 3. *Sample spectrograms (frequency-time representation of sound intensity, where lighter colors represent more intense sounds), from the ORCA2015 location (left) and drifting hydrophones (right). The ORCA figure extends to 96 kHz and is in logarithmic format, with a time duration on the order of 1 minute; the drifter figure extends to 200 kHz and is in linear format, with a time duration on the order of 30 minutes.*

variability, a specific arrangement of instrumentation was used to collect data in 2014-2015: a single-channel moored hydrophone (HF2014-2015) was deployed in a sheltered location away from the strongest flows, a 5-channel moored hydrophone array (ORCA2015) was deployed in a high-flow location where pseudonoise could be evaluated, and a 2-channel hydrophone array (Drifter) was deployed in a series of consecutive drifts to decrease the relative motion between the water and the instruments. Additional local instrumentation provided concurrent datasets that were used to support soundscape analysis: flow speed data from a moored Acoustic Doppler Current Profiler (ADCP) and meteorological data from the local Environment Canada weather station. The relative locations of these instruments are shown in Figure 2.

The genuine and literal phonies, and the role of tidal currents

Sound sources can be visually identified based on established characteristics such as frequency range and duration. A sample compilation of identified signals is shown in Figure 3. These figures, called spectrograms, are an intensity representation of sound over time, where the x axis is time, y axis is sound frequency, and colors are sound amplitude. While signals are sometimes identified aurally or through algorithms, high variability of sources and potential masking effects can often lead to false or missed identifications; as such, the present study focused on visual examination of spectrograms. As demonstrated in Figure 3, this visual interpretation approach can be used to distinguish multiple signals occurring simultaneously. The data can then be filtered to isolate each signal for more detailed analyses. The analysis reveals a soundscape that has measurable anthropophony, biophony, and geophony throughout, and that the relevant contributions and magnitudes of these categorical sources changes in space and time.

At the northern entrance of the Passage (Figure 3, left), a variety of marine mammal sounds are distinguishable at frequencies less than 20 kiloHertz (kHz; within the range of typical human hearing); identified species include humpback whales, Atlantic white-sided dolphins, and right whales. An evaluation of pseudonoise effects at the ORCA2015 instrument location (Figure 3) suggests that these non-acoustic signals – literal phonies, by definition – exist up to frequencies of several hundred Hz, with pseudonoise amplitudes closely related to local flow conditions. As many mammals produce sounds within this frequency range, there is a risk that intense pseudonoise during strong currents could inhibit the detection of marine mammal sounds.

Data from the drifting hydrophones and moored hydrophones show that in the northern half of the passage, sound from mobile sediments is a dominant source over a wide frequency band. The amplitude of sound is closely related to changes in flow speeds, resulting in maximum noise levels during periods of peak currents. The location of peak sound levels occurs near a region of known gravel waves on the seabed, where large volumes of loose sand, gravel, and shell fragments move during each tide. Away from the gravel waves region, sediment noise is almost undetectable and the acoustic energy becomes dissipated through scattering and absorption. The spatial variability of this source has implications for the detection of high-frequency marine mammal sounds. Harbor porpoise clicks in particular could become masked by the intense sediment noise in some regions.

Silence of the bubbles

Energy inputs at the air-sea interface, specifically related to changing weather conditions, can be loud and disruptive to the underwater soundscape. The extents of these effects were evaluated using sound and wind speed datasets collected during a storm event in October 2015. Contrary to what might be expected, it was found that periods of sustained high winds were associated with lower received noise levels at frequencies greater than 20 kHz. Under normal conditions, wave formation in Grand Passage is minimal, but propagating (and breaking) waves form during high wind conditions. The familiar "beach soundtrack" of breaking waves and pounding surf would seem to indicate *more* noise during high wind conditions. Breaking wave crests do generate sound, but they also generate bubbles - a lot of bubbles. High concentrations of bubbles (bubble clouds or plumes) can result in a decreased sound propagation speed, which disrupts the propagation patterns of sound waves by refracting wave paths upward (the schematic in Figure 4 shows a conceptual representation of this effect). The result is that sound generated from sediment collisions in Grand Passage is "redirected", in this case away from the hydrophone receiver. Recorded levels are thus decreased compared to the low wind or average conditions, even if the sound levels at the original source (mobile sediments in this case) are unchanged. The most significant differences in geophonic characteristics were found to occur when the direction of high winds was in opposition to the direction of current flows – these conditions yield steeper wavefronts and more breaking waves, increasing the concentration of bubbles in the water column.

Kluskap's bathtub symphony

The Grand Passage soundscape is a dynamic, complex compilation of sources that are constantly changing in space and time. It is an uncoordinated yet harmonious symphony of propagating acoustic energy subject, in many ways, to the whims of the Fundy tidal currents — tides that, as Mi'kmaq legend has it, were created after Kluskap decided he wanted to take a bath. And it is the author's hope that the ever-present harmony of the natural soundscape, and its place within the ecological and cultural significance of the Bay of Fundy, will serve as a model for a respectful and harmonious approach to tidal energy development in the region and throughout the world.

THIS RESEARCH WAS FUNDED BY THE NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL (NSERC), NATURAL RESOURCES CANADA (NRC), NOVA SCOTIA BUSINESS INC. (NSBI), AND FUNDY TIDAL INC.

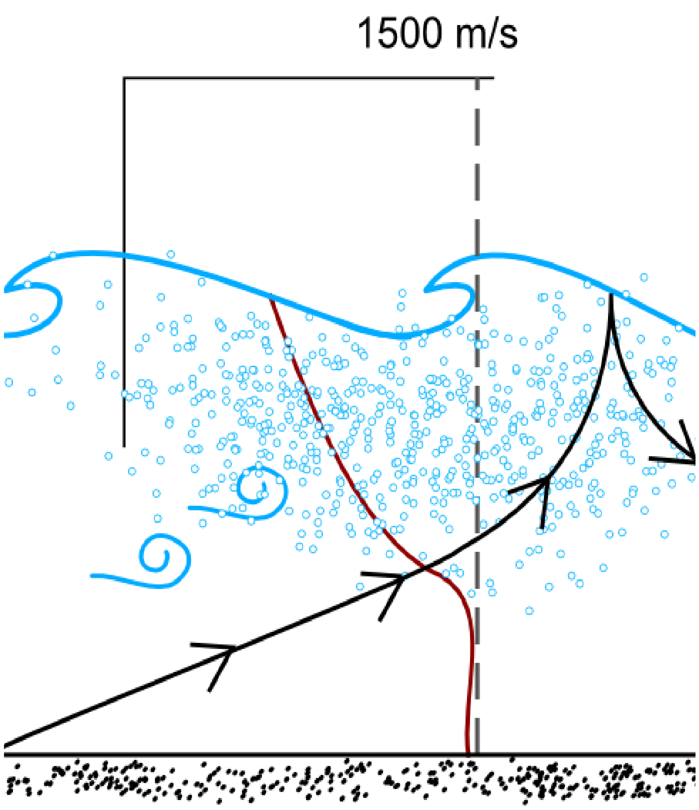


Figure 4. *Effect of bubbles on sound wave propagation paths. The sound speed (red line) decreases near the surface, causing ray paths to curve upwards and away from a bottom-mounted hydrophone receiver.*

Anne Lombardi

Hailing from the coastal town of Seaforth, Nova Scotia, Anne finds balance where the ocean meets the forest, and seeks guidance from nature's wisdom, magnificence and resilience. A dedication to sustainable development led first to a degree in environmental engineering at Western, followed by practice in the field of green building design in Ottawa. After years of seaside deprivation, she returned to Nova Scotia and joined Dal's ocean acoustics research group led by Dr. Alex Hay. She completed her master's degree in 2016, and now teaches in the energy sustainability program at Nova Scotia Community College (NSCC). When time allows, Anne typically reverts to wandering in the woods, pondering the complexity of the world, and tinkering around the West Paradise homestead she shares with her partner Derek.

Risky Business

Plankton movement and encounter rates

Kevin Sorochan

Movement facilitates interactions between organisms and their environment

Movement is an essential requirement for the reaction of chemicals, absorption of nutrients, acquisition of food, and reproduction of organisms. Movement is so important because it facilitates encounters, which initiate interactions between an organism and its environment. Try to imagine yourself in a world without encounters. You would not eat any food, or have any friends or lovers. Life would be very dull. In fact, life would cease to exist.

In ecology, the rate of encounter among predator and prey is an important source of variability in the rate of feeding and mortality due to predation. The dynamics of plankton populations are extremely sensitive to variability in the mortality rate, and predation is thought to be a primary source of mortality. Movement is advantageous for organisms because it increases the chances of encounters with food, but it is also "risky" because it increases the chances of encounters with predators. Certain types of movement are more risky than others. In a uniform environment, travelling along a straight path will maximize the probability of encountering both food and predators. Travelling along a convoluted path is less risky, but at a cost of a lower probability of finding food.

Classic encounter rate models that are commonly used to predict rates of feeding or predation in plankton ecology are based on certain assumptions of movement. I used a computer model to describe what happens when these assumptions are not true. I also quantified metrics of swimming behaviour from swimming trajectories of zooplankton in the laboratory to evaluate their "risky" behaviour.

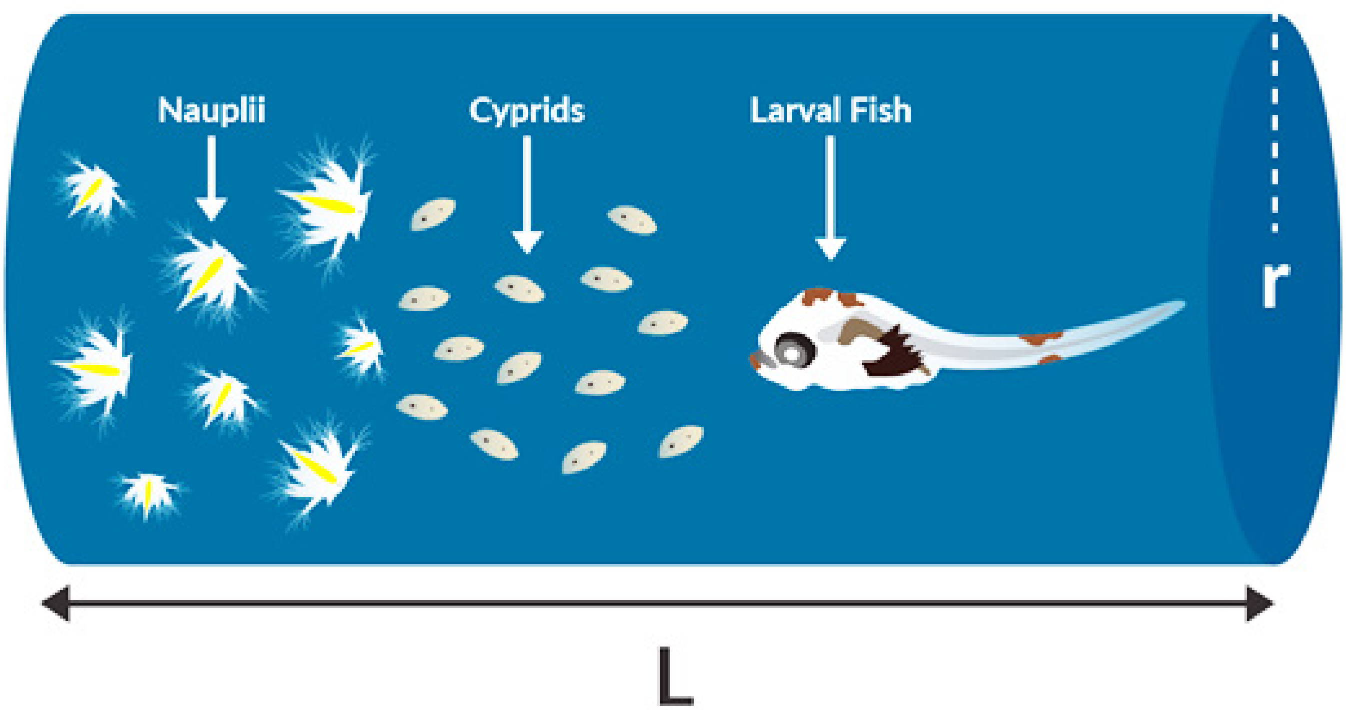


Figure 1. *The volume scanned for prey by a fish predator with prey detection distance, r, travelling over a distance, L. The maximum clearance rate is the volume scanned divided by the duration of the trajectory.*

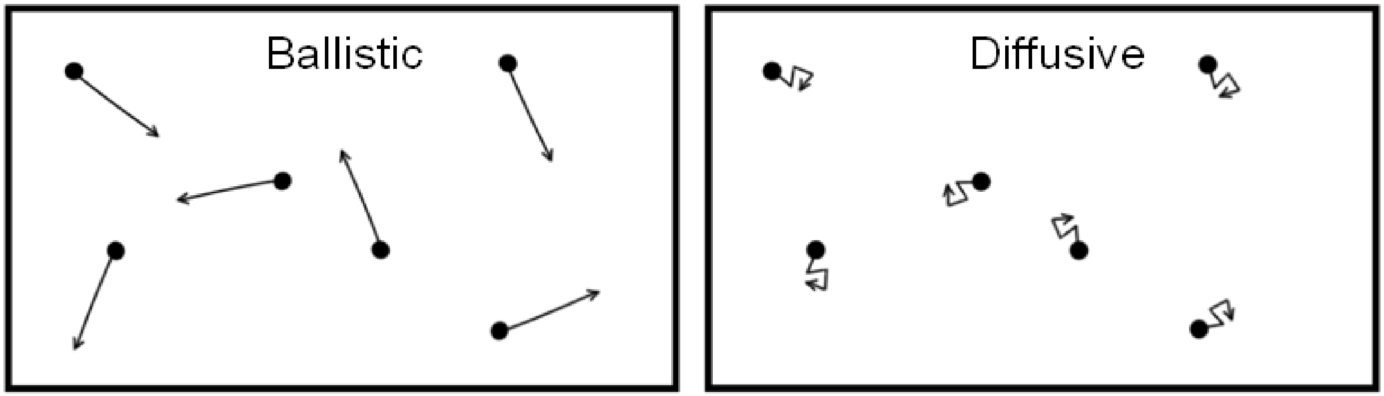


Figure 2. Schematic of ballistic and diffusive movement. In ballistic movement, the path is straight-lined, and the direction of each particle is random. In diffusive movement, a new direction is selected randomly at each step forward in time, resulting in a convoluted path.

Classic encounter rate models and their assumptions of movement

The equations used to predict encounter rates in plankton ecology have been adopted from the theory of reaction rates. For a reaction with two reactants, A and B, the reaction rate, r, consists of the product of the reactants concentrations and a rate constant k (r = [A][B]k). In the context of encounters among plankton, the reaction rate is the encounter rate, the reactants are the predator and prey, and the rate constant, referred to as the "maximum clearance rate", is the rate at which a volume of water is scanned for prey by the predator assuming all prey that are encountered are consumed. Maximum clearance rate is dependent on the relative movement of predator and prey, and the distance from which a predator can detect prey (Figure 1).

In 1860, James Clerk Maxwell published an equation for the rate of collisions among molecules in a gas. In Maxwell's model, molecules move along linear trajectories in random directions. This movement is referred to as "ballistic motion" (Figure 2). In 1916, Marian von Smoluchowski published an equation for the rate of coagulation of particles suspended in solution. In Smoluchuwski's model, particles change their direction of travel in random directions at very short length scales relative to the length scale of the observer. This movement is used to describe diffusion, and is referred to as "diffusive motion" (Figure 2).

Classification of movement (ballistic, diffusive, or in between) is dependent on the following two length scales: (1) the mean length of the path between reorientations in random directions, referred to as the "persistence length"; and (2) the length from which the prey can be detected. Imagine yourself observing a vehicle driving aimlessly through a city. If you were at an altitude of several hundred meters, the path of the same vehicle would appear diffusive; however, if you were standing on the sidewalk, you would perceive the movement of the same path as ballistic (a straight line). In this case, the persistence length of the vehicle is the length of a city block, and the detection distance is the distance between you and the vehicle. In the plankton, ballistic movement can be used to approximate a predator moving through the water column along a relatively straight path while searching for prey (Figure 1). On the other hand, diffusive movement can be used to describe the flux of nutrients into a suspended phytoplankton cell.

The classic models derived by Maxwell and Smoluchowski are valuable tools for the mechanistic prediction of encounter rates, but how do these models perform if their assumption of movement is invalid? That is, what are the consequences of assuming ballistic or diffusive movement when the lengths of persistence and detection are similar to one another? It is likely that this situation often occurs in nature. Solving this problem mathematically from first principles is apparently very difficult, and the only available equations represent approximations or best guesses.

Describing the diffusive to ballistic transition using a computer model

I described variation in the maximum clearance rate with the detection radius of the predator, persistence length of prey, and time by writing a computer program that simulates a motionless predator feeding on moving prey. I simulated prey movement using a "correlated random walk" model, which bridges the gap between ballistic and diffusive movement by allowing for the parameterization of a persistence length (average length between reorientations in random

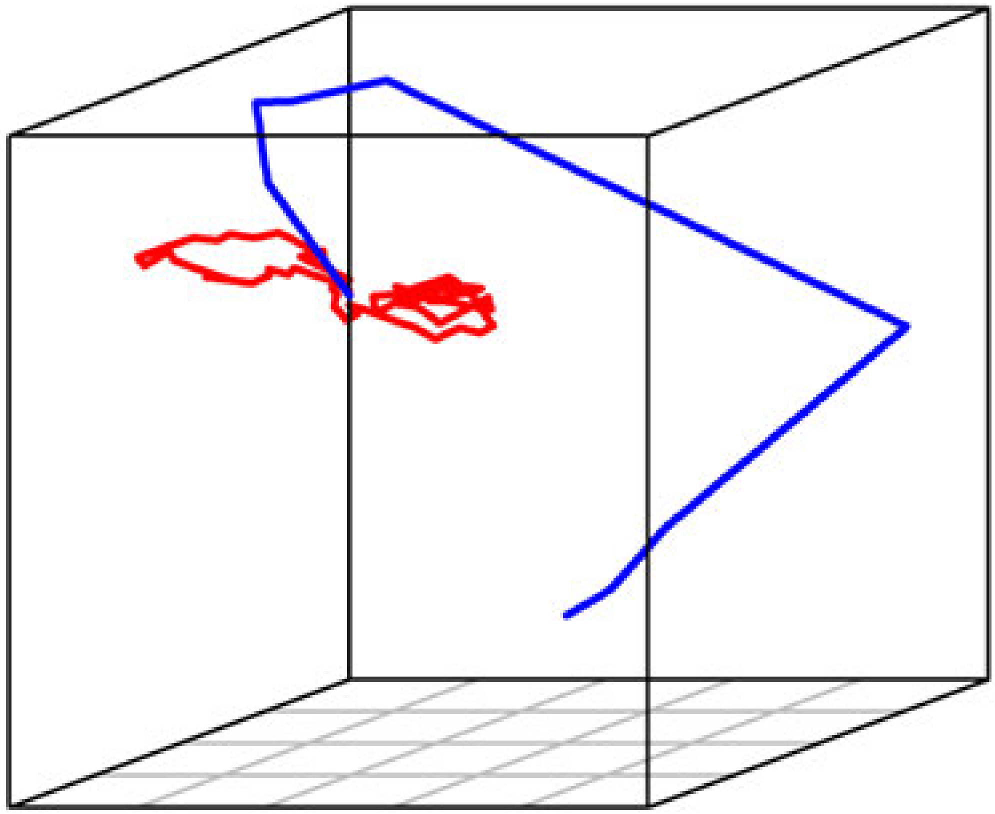


Figure 3. Examples of two paths generated from correlated random walk. The persistence length of the blue path 20 times greater than that of the red path.

directions). The paths of two prey items characterized by different persistence lengths are shown in Figure 3. I used data from my model to provide a description of the maximum clearance rate over the transition from diffusive to ballistic movement, and recommend the use of a correction to the classic models developed by Maxwell and Smoluchowski.

Analyzing swimming paths of larval barnacles in the laboratory: do feeding stages exhibit "riskier" behaviour than non-feeding stages?

Barnacles release larvae into the water column where they progress through a series of stages before settling on a hard substrate and metamorphosing into a young adult stage. There are two distinct larval forms: the nauplius and cypris. The nauplius feeds to accumulate an energy reserve needed for survival to the young adult stage. The cypris does not feed and is adapted for settlement. I measured the swimming speed, persistence length, and persistence time (persistence length divided by mean swimming speed) from video-recordings of swimming paths of nauplii and cyprids in the laboratory. This was accomplished by tracking larvae over time and fitting their observed distance travelled to that predicted from correlated random walk. Given that the nauplius must feed, I predicted that this stage would exhibit riskier behaviour than the cypris, as indicated by a larger persistence length of nauplii than of cyprids.

Examples of trajectories from the nauplius and cypris stages are shown in Figure 4. The paths of nauplii were characterized by meandering loops, whereas those of cyprids were characterized by zig-zags resulting from jumps and passive sinking. I found that nauplii generally exhibited higher persistence times than cyprids. However, the nauplii were also characterized by much lower mean swimming speeds, which resulted in similar persistence lengths among nauplii and cyprids. I found that temperature can have an impact on swimming behaviour, and potentially encounter rates with predators, as both swimming speeds of nauplii and the persistence time of cyprids increased with temperature in my experiments.

I measured the persistence length assuming that swimming was characterized by correlated random walk, and assumed that the paths are not organized in repetitive or oscillatory structures, which is likely an oversimplification. Other studies have shown that trajectories characterized by swimming and sinking (cyprids in my study) are far less risky to encounters with predators than looping patterns (nauplii in my study). Therefore, I suspect that the actual difference in predation risk between nauplii and cyprids is larger than that inferred from differences in persistence length from my study.

Ecological significance of directional persistence in movement

Directional persistence in swimming can be used to predict encounter rates between populations of predators and prey, and swimming behaviours that may emerge from the trade-off that occurs when an organism must risk predation to find food. Species-specific predictions can be obtained by measuring directional persistence from video of zooplankton swimming in the laboratory. For example, persistence lengths of larval barnacles can be used in my computer program to predict variability in encounter rates with a particular predator. Predictions of encounter rates can be used to further predict predation rates, or evaluate the link between life history strategy (feeding, non-feeding) and swimming behaviour. It is thought that mortality reduces the abundance of larval stages of marine benthic invertebrates by up to 99%. This work will improve the ability to develop hypotheses regarding the effect of predation on larval abundance and behaviour in the sea.

THIS RESEARCH WAS FUNDED BY NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL (NSERC) AND DALHOUSIE UNIVERSITY.

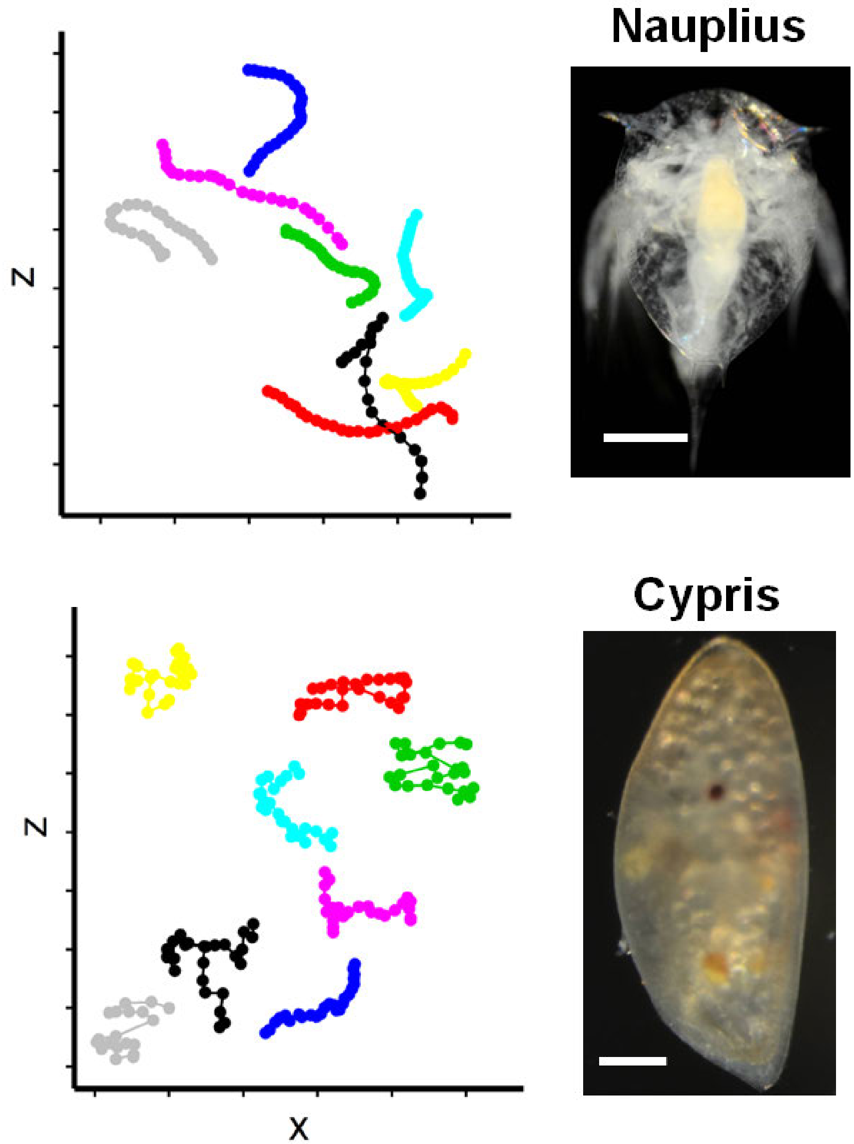


Figure 4. Examples of paths from the nauplius and cypris stage of larval barnacles in vertical (z) and horizontal (x) dimensions over 6 seconds. Tick marks on both axes correspond to increments of 4 millimetres. Scale bar is 0.2 millimetres.

Kevin Sorochan

Kevin became inspired to study marine science when exposed to the diversity within the “hidden world” of marine invertebrates and seaweeds along the shores of Vancouver Island in British Columbia, where he was born and raised. Kevin immediately wanted to know everything about these organisms and how they interact with their environment. He pursued his interests as an undergraduate student at the University of Victoria and Bamfield Marine Science Centre, and as a MSc student in Biology at University of Prince Edward Island. Kevin recently completed his PhD at Dalhousie, working under the supervision of Dr. Anna Metaxas. When not experimenting on larval marine benthic invertebrates, collecting zooplankton from the ocean, or working diligently in his office, Kevin is outside on a wacky adventure, reading a book, tasting a beer, or shredding on his skateboard.

What Does a River Deliver?

Estimating the global delivery of nutrients from rivers to the open ocean

Jonathan Izett

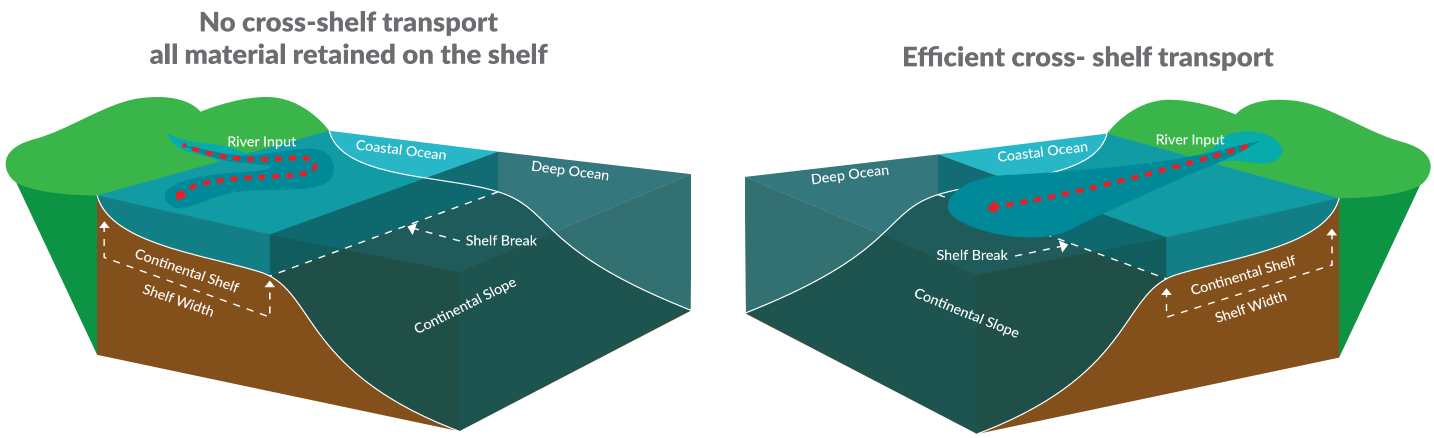


Figure 1. *Left Panel: Plumes that are strongly deflected by the Coriolis force (high latitudes) and are small compared to the width of the shelf are limited in their cross-shelf transport. Right Panel: plumes that weakly deflected (low latitudes) and large compared to the shelf width transport material efficiently across the shelf break to the open ocean.*

The importance of rivers and their nutrients

I wouldn't be the first one to write that rivers are the arteries of the Earth; however, it is still an apt metaphor. Like arteries, rivers are vital for the health and functioning of our planet. Instead of blood, they carry water across continents, connecting different regions, and transporting materials from one place — mountain springs, majestic lakes, historic cities — to another. In many cases, this *other place* is the ocean, with thousands of rivers delivering 1.2 billion litres of fresh water to the coastal ocean every second. (Fun fact: that's the equivalent of 2 billion extra-large "Double Doubles" — roughly half the total amount of coffee consumed in Canada annually — every second!)

As with arteries, it isn't just the life-giving fluid that is transported, but also nutrients (often entering the river as runoff from farmland), toxins, and other suspended particles (such as sediments). Knowing where all of these materials end up is an important factor in understanding the overall health and functioning of the system. Focused management and response strategies, for example, can be directed with knowledge of sediment and pollutant pathways.

Nutrients present a different set of problems. In areas where nutrient delivery to the coastal ocean is high but export to the open ocean is inefficient, nutrients can accumulate in the shallow coastal waters of the continental shelf (see Figure 1). Increased nutrient availability can then lead to increased primary production by phytoplankton (a process called eutrophication). Unfortunately, with the increased production comes an increase in dead organic matter sinking to the bottom. As the organic matter is recycled by bacteria within the shallow water, oxygen is consumed, which can eventually lead to a condition known as hypoxia: a state of very low oxygen which is harmful to ecosystems. Most organisms are unable to survive in hypoxic conditions, resulting in lost species diversity and habitat. The Gulf of Mexico into which the Mississippi River flows (draining over 50% of the continental US; much of which is farmland) is one region where the problem is particularly apparent. Globally, things are getting worse. Nutrient loads in the coastal ocean are much higher than pre-industrial levels and are continuing to increase due to human activities, such as land-use changes and the growing use of fertilizers to feed the expanding world population.

Where all of this riverine material eventually ends up is strongly determined by the path of water within river plumes. As the fresh water from a river flows into the salty, denser ocean, it remains at the surface and spreads out as a buoyant plume. Due to the Earth's rotation, the plume is deflected by the Coriolis force; a result of low latitudes moving faster than higher latitudes due to a larger diameter about the Earth's axis — just like the edges of a record player spin faster than the inside. This apparent force results in the flow turning perpendicular to its motion: to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This effect is stronger with increasing latitude such that plumes near the equator are barely affected and flow directly away from the coast, whereas plumes at higher latitudes are turned much more. The turning of the plume results in the formation of two distinct regions: a rotating bulge near the mouth, and a coastal current that flows along the shore (Figure 2).

On a smaller scale, local weather and tidal conditions can play a role in influencing plume circulation. Wind, for example, can blow a plume offshore, enhancing export of material to the open ocean, or it can conversely restrict offshore spreading if the wind is directed toward the coast.

In my research, I used computer models to answer such questions as: What influences the fraction of material transported across the shelf to the open ocean? Knowing only, for example, a river's discharge and location, can the transport be described with a simple model? And, how much total material is transported in river plumes to the open ocean?

Simulating river plumes with numerical models

Models are extremely valuable in oceanography — the computer kind, that is, although we are a good-looking crowd too! They enable us to supplement observations by providing increased resolution in time and space beyond what is possible with traditional observational field studies. Imagine trying to take a bucket of water from the ocean every ten kilometres, and every few hundred metres deep...impossible! Not only would you need a lot of storage space for all that water, it would also prohibit you from having any semblance of a social life given the time commitment. With computer models, however, we are now able to explore the oceans on these scales, and indeed, even better! Models also allow us to travel through time — both exploring past climates and projecting how things might look in the future — as well as enabling experiments to test what if scenarios: changing conditions in the simulated ocean to understand how it could affect our real ocean.

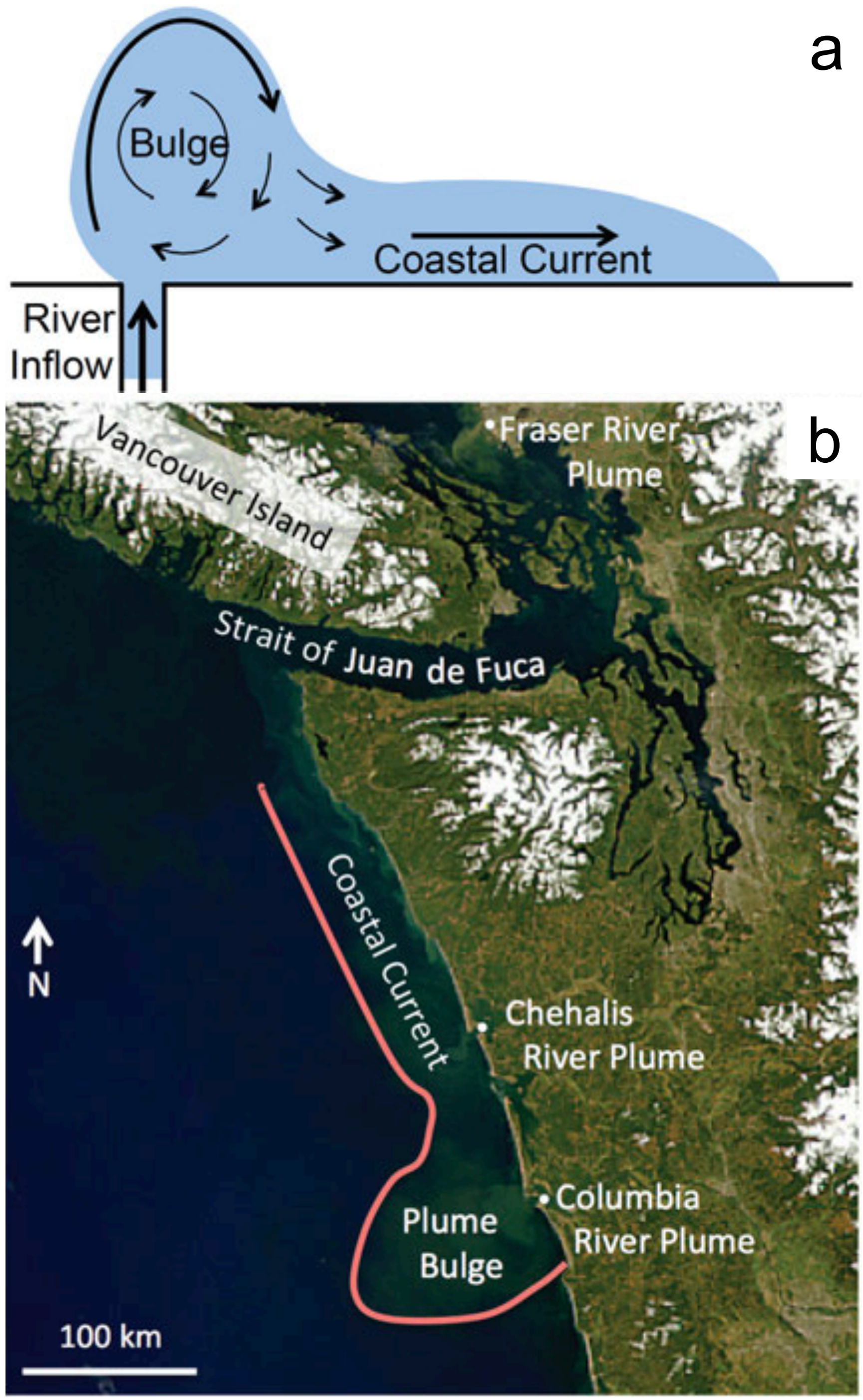


Figure 2. a) An idealized river plume deflected by the Coriolis force in the Northern Hemisphere. b) A real river plume (the Columbia River) as seen from space with NASA's SeaWiFs instrument. The plume, roughly outlined in pink and visible due to high sediment and chlorophyll loads, forms a bulge region and is deflected to flow north along the coast to Vancouver Island. (Satellite Image: http://visibleearth.nasa.gov/view.php?id=52924)

Unfortunately, all models also have their limitations and drawbacks. In the case of river plumes, the resolution of global models is still too coarse due to current limits in computational power, and simply cannot capture the relatively small features of the plumes themselves. As a result, most global models (such as the earth system models used to pre-

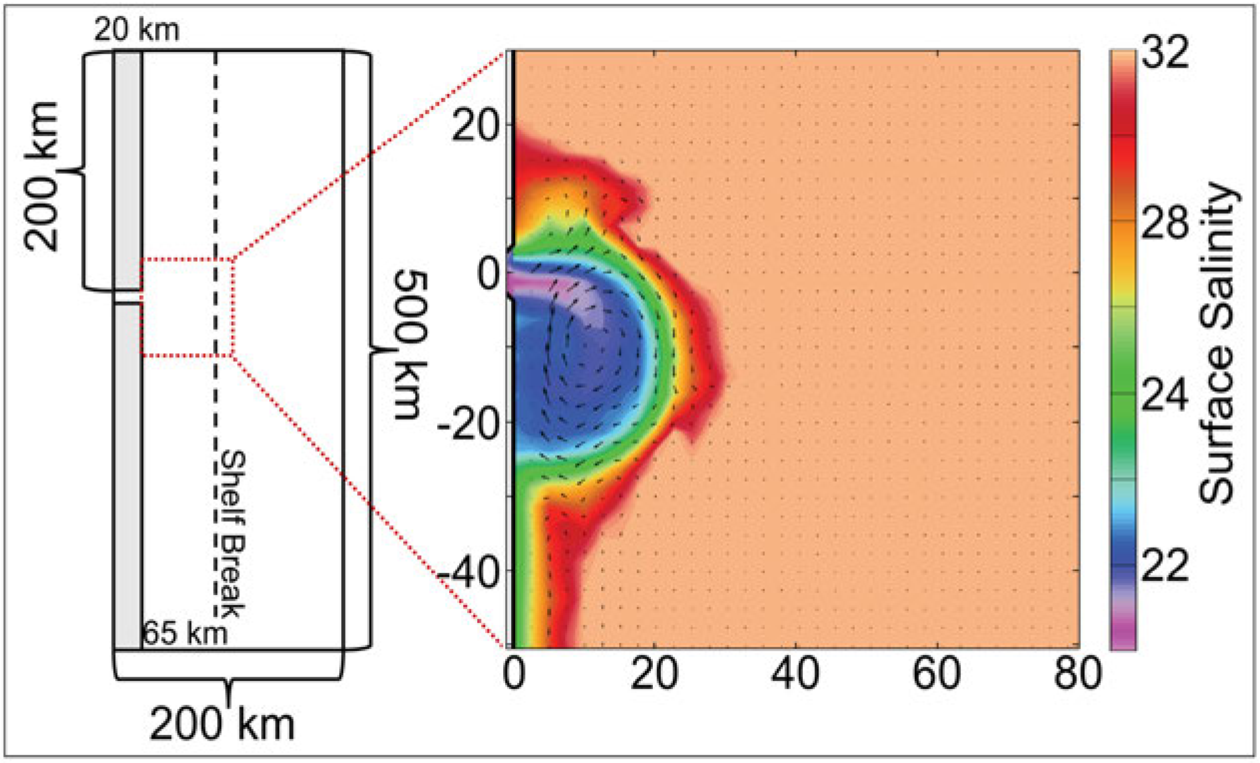


***Figure 3.** The idealized river plume model domain: 200 km in the offshore direction and 500 km in the along-shore, with a freshwater input (the river) 200 km from the northern boundary of the domain. Inset shows the simulated salinity within the plume after 15 days of simulation at 45° latitude.*

dict future climate) adopt an all or nothing approach for riverine inputs to the open ocean, assuming everything makes it across the shelf, or that nothing does. Both approaches misrepresent nutrient transport. While models have been successfully developed for individual rivers, to do so for the thousands of rivers on a global scale is obviously not practical. That's where my work comes in.

In order to investigate the dynamics of river plumes, I performed a series of numerical simulations under varying conditions. My laboratory, so to speak, was a rectangular coastal ocean set up to represent a simplified river plume system (Figure 3), with fresh water entering through a channel at the coast. Within this setting, I changed the latitude-with different forcing from wind and tides-producing a total of 224 simulations. By individually adjusting the external conditions in the different simulations, I was able to determine the influence of individual factors, which would otherwise be impossible in the real world.

From simulations to real world estimates

From the simulations, I was able to develop simple relationships to estimate how much of a river's material is transported across the shelf within a plume using only basic properties: the river's discharge, its latitude, and the local width of the shelf. Using these relationships, I calculated the cross-shelf transport for all rivers around the world that flow into the ocean.

Overall, the most efficient export occurs for rivers at low latitudes and narrow shelves (Figure 4). Near the equator, river plumes flow much further offshore due to the weaker Coriolis force, meaning a higher proportion of material is able to reach the open ocean. At the same time, a narrower shelf (such as along the active subduction zone on the west coast of North America) means the plume has less distance to travel and can still make it to the open ocean, even with stronger deflection. On the other hand, the wide shelves of North America's east coast mean that export is highly inefficient.

Near the equator, export is very high (in many cases, greater than 90% efficiency), but the deflection due to the Coriolis force results in limited cross-shelf export such that in the mid- to high latitudes, very little material makes it to the open ocean from river plumes. In a global sense, less than 60% of all riverine material that is delivered to the coastal ocean actually makes it across the shelf. The remaining 40% of material retained on the shelf can subsequently have serious implications for coastal systems if there are no further processes to dilute the incoming material.

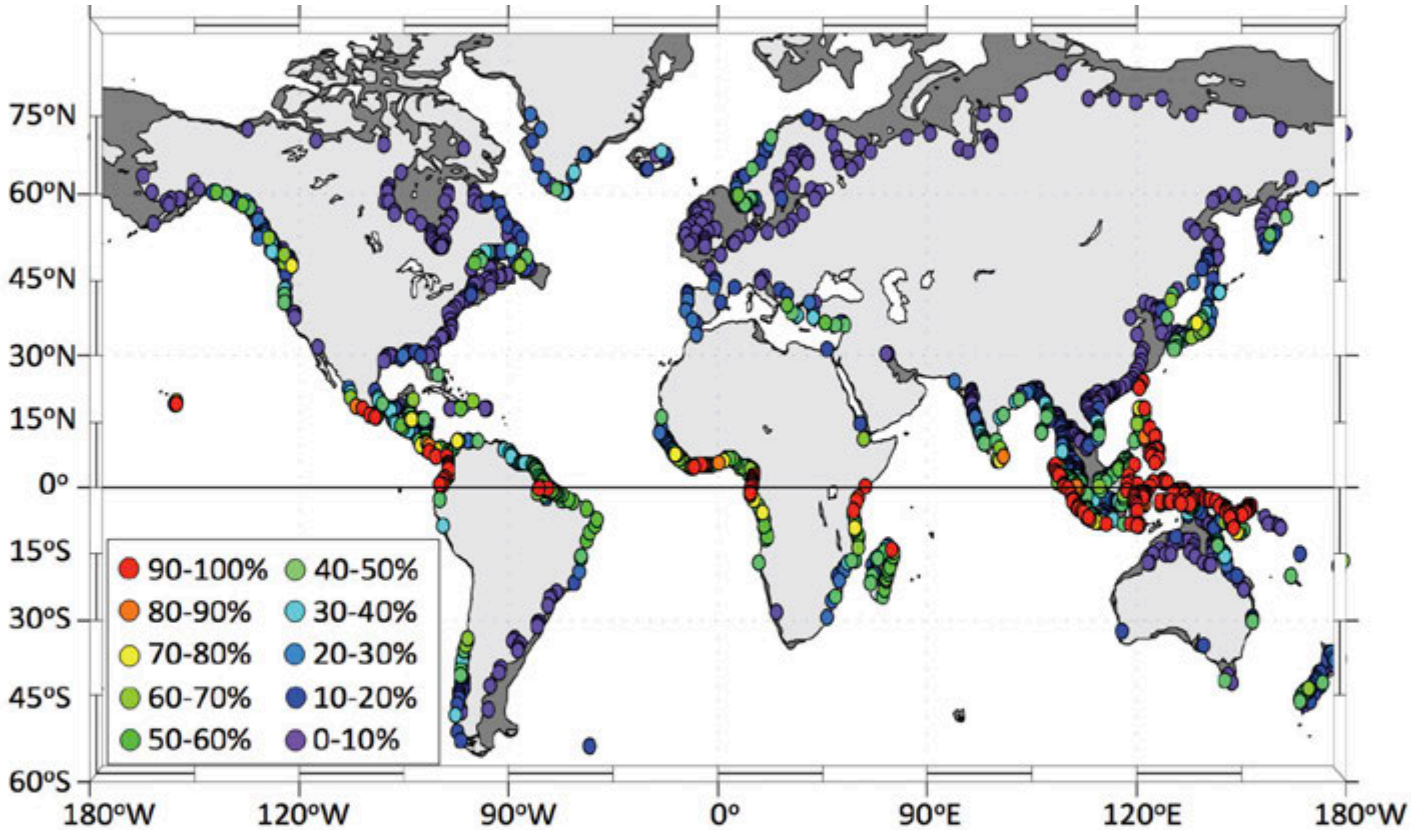
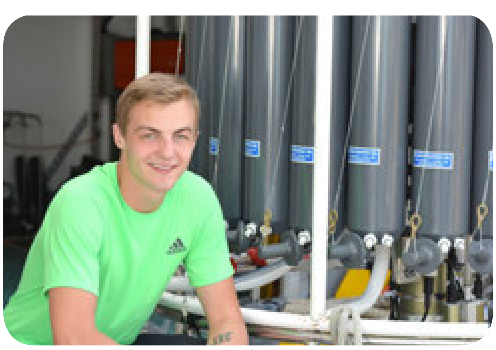


Figure 4. *Estimated percentage of riverine freshwater that is exported across the continental shelf for all rivers that discharge into the ocean. Shelf regions - to depths of 200 m - are shown in dark grey.*

What does it all mean?

The results of my research help work toward a greater understanding of oceanic nutrient cycles, from local to global scales. The simple relationships I developed allow for a quick and easy way of estimating whether nutrients are retained on the shelf or exported to the open ocean for any river, aiding in the identification of areas at risk of eutrophication and hypoxia. At the same time, global estimates provide a clearer picture of how and where nutrients are delivered to the open ocean, improving upon the all or nothing approach commonly used. When you consider the sheer volume of material entering the ocean, even a small difference in percentage can have a big impact! Ultimately, these improved estimates can be incorporated into global ocean models (including climate models), allowing for a better representation of the global nutrient cycle. When it comes to oceanic nutrients, my research doesn't answer everything, but it does help us to better understand what a river delivers...

THIS RESEARCH WAS FUNDED BY THE NSERC (CGS-M SCHOLARSHIP) AND THE NOVA SCOTIA GRADUATE SCHOLARSHIP (NSGS, MASTER'S LEVEL).



Jonathan Izett

Jonathan's love for the ocean was instilled at a young age, encouraged through his naval architect father and his mother who takes every opportunity to jump into waves (no matter their size or the water temperature!). He has lived all across Canada, but spent most of his time on the west coast in Victoria. Jonathan completed his BSc in Physics and Ocean Sciences at the University of Victoria before moving across the country to do his MSc at Dalhousie University under the supervision of Dr. Katja Fennel. He is now living in the Netherlands with his wife, where he is working toward a PhD at the Delft University of Technology.

A Flash(Flood) in Time

The fate of flashflood deposits on the shallow shelf in the Gulf of Eilat-Aqaba, Red Sea

Alysse Mathalon

Figure 1. *Underwater photograph of a flashflood entering the Red Sea in February 2013. Photo credit: Gil Koplovitz*

Uncovering the mystery

Imagine yourself surrounded by a still, serene, silent desert. There is complete peace and quiet, with nothing but exquisite rock formations around you, seemingly unmoving. This is the experience you typically have in the southern part of Israel's Negev desert. On occasion though, usually in the changing of seasons, rains can shower, at times bringing in more water than the desert can absorb. In a flash, dry river beds transform into rushing rivers, growing larger and travelling faster as they accumulate water, flowing seaward. When these floods occur far enough to the south, they flow into the Gulf of Eilat-Aqaba in the Red Sea, through Eilat, Israel's most southern city. These floods can bring tens of thousands of tonnes of desert sediment into the sea within hours (Figure 1)!

To us, these flashfloods are mysterious, as very little is known about how often they occur and in what magnitudes. The record of flashfloods entering the Red Sea from Eilat is only 23 years old. This short length of time is especially apparent when confronted by the 500-million-year old desert mountains visible from my window. Floods are the dominant supply of fresh water to the desert, and are important for allowing life to persist in the otherwise dry environment. Flashfloods are relevant to study due to their major contributions of sediment, nutrients, and pollutants to the sea on very short timescales. They also have the capacity to transform geological landscapes, and past climates can be inferred through their frequencies and magnitudes.

For my research project, we looked to the sediment layers below the seafloor to tell us stories of flashflood history. Are there climatic patterns in flashflood events that are not visible to us within our lifetimes? Our Canadian-Israeli research team set out to discover if we can find signals of flashflood events within the sediment record of the Red Sea from the past 2000 years. To help determine if flashflood deposits become preserved within the shallow seafloor, three wise marine geologists posed to me a few “simple” questions: What occurs to flashflood deposits upon settling on the seafloor? Do they remain intact to get buried by subsequent floods, and thus become preserved within the sediment record? Or do they get mixed and removed by the local biota and water currents, erasing their distinct presence? These I set out to answer.

Time to get muddy!

We conducted underwater experiments at 13 metres water depth, just offshore of the Kinnet Canal, the primary entry point of flashfloods to the sea from Eilat (Figure 2). Though fringing coral reef ecosystems are typical along the shallow shelf of the Red Sea, the seafloor at our study site is comprised of sand due to its location at the mouth of the (mostly dry) riverbed.

One of the focal experiments we conducted was to observe changes that occurred to two flashflood deposits after they settled on the seafloor, by collecting sediment samples every three months throughout the year after they were deposited. To collect these tri-monthly samples, we dived at our site and took short sediment cores from the seafloor. Cores were taken by pushing a plastic tube into the seafloor, placing a plug on the top, using the suction to pull the tube filled with sediment out of the seafloor, and plugging the bottom. Voilà! Time in a tube. Sediments deposited from floods leave a telltale layer of fine grained silts and clays on the seafloor. Each core taken was sliced by centimetre, with a subsample taken from each to measure the grain size. We got the percentage of fine sediments down each core, allowing us to track the presence of flood deposits.

Figure 2. Local (A) and regional (B) diagrams showing the location of the study site, designed by Ákos Kálmán. In the local map (A), the Kinnet Canal outlet is shown by the blue line shoreward of the Sampling Site. All blue lines represent wadis (dry river beds).

In addition to this experiment, I was responsible for investigating the major processes controlling the movement of flashflood deposits after their deposition by studying mechanisms of sediment removal and mixing. To see if water currents were responsible for kicking up fine sediments, we placed an instrument on the seafloor to track current speeds. To observe the role fish played in resuspending sediment, we deployed GoPro cameras at the site, photographing in 30 second intervals.

Lastly, to measure the depth and magnitude of bioturbation, which is the mixing of sediment by organisms in the seabed, a larger, more thoughtful experiment was required. Our study area is teeming with life. These animals are mostly out of sight, but the homes they create out of the seafloor remind us of their presence. They bioturbate the sediments by excavating mounds of sand, holes, and networks of tunnels hidden beneath the seafloor like the inner workings of a city. To study this, we tracked surface sediment movement using tracers made of fine sediment that fluoresced green under ultraviolet light (UV). I began by taking 27 cores from the study site, and on each one I placed a layer of tracer. We developed a prototype to transplant sediment cores back into the seafloor. After much practice, all sediment cores with tracers were transplanted into the seafloor in specific locations. A few weeks later, I took cores from the seafloor in the same locations where I initially transplanted the cores. At the lab, each core was sliced by centimetre. Once all slices were dried, each centimetre containing tracer was crushed into a powder. Subsamples from each centimetre were photographed under a microscope using UV light, and the area of fluorescence was determined in each photograph, providing a value on how much tracer was within each centimetre of each core.

What we hoped to get out of the bioturbation experiment was to observe how the tracer travelled within the seabed, and how much remained from the original amount. This would give us insight into the extent surface sediments were mixed down below and were removed from above, adding more pieces to the puzzle in discovering what occurs to flashflood deposits.

What did we find?

A wise woman once told me, “Never take more than one core”. Why? Because things get complicated! We learned from the tri-monthly sediment cores that there was a whole lot of variation in the grain size profiles within the sediment. The majority of the flood deposits disappeared from the surface of the seafloor within months. Some cores showed preservation of floods, indicated by a peak of fine sediment around 10-20 centimetres depth. These were likely from floods from the past five years. Other cores had completely uniform grain sizes, suggesting no flood preservation. These observations revealed the complexity of the seafloor as a product of the local diversity of biological activities.

We observed that water currents were weak, and were therefore not a dominant cause of sediment resuspension off the seafloor during our experiment. This suggested that biology was the primary driver of sediment resuspension and mixing. The GoPros provided footage of fish kicking up sediment. When this happens, the very fine particles flow away with the currents until settling down again. The extent of sediment resuspension from fish was not quantified, but we observed it was occurring.

From the bioturbation experiment, an error that was made when transplanting the cores into the seabed led to an interesting result. When transplanting, I placed some of the cores with their tracer layers in line with the seafloor (surface transplants), and others a few centimetres (> two centimetres) below the seafloor (deep transplants). The deep transplants left a small hole in the seafloor, which quickly became filled with the surrounding sediment, burying the tracer layer. We found that in cores with surface transplants, the tracer moved more uniformly down the core, and experienced enhanced removal compared to tracers with deep transplants (Figure 3). This tells us that the strongest mixing and removal occurred in the top two centimetres of the seabed. In the end, the results were still valuable in interpreting the fate of flashflood deposits. Phewf!

Are flood deposits preserved?

The answer is both yes and no. In some locations of the seafloor, peaks of fine sediment found at depth are evidence of preserved floods. However, local removal of flood deposits from biological activities appears to be a very fast and efficient process. Despite removal and mixing, we still found local preservation of flood deposits. Flashflood layers can only become preserved if they are buried to depths in the seabed where they are no longer affected by physical or biological processes. This can occur if (1) flood deposits are thicker than two centimetres, as sediment mixing and removal is less intense deeper than two centimetres, (2) floods are deposited within deep holes, or (3) deposits are quickly buried by sediment mounds created by organisms, or by ensuing flashflood deposits (Figure 4). From our observations of the shorter sediment record, we did not find distinct flood layers.

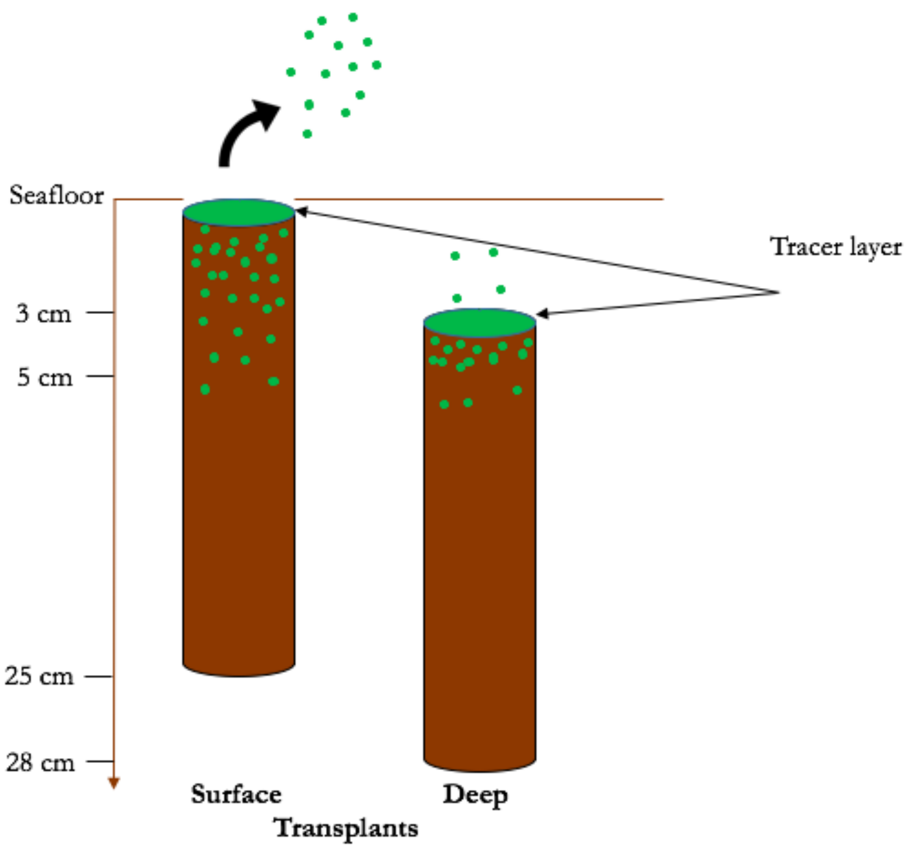
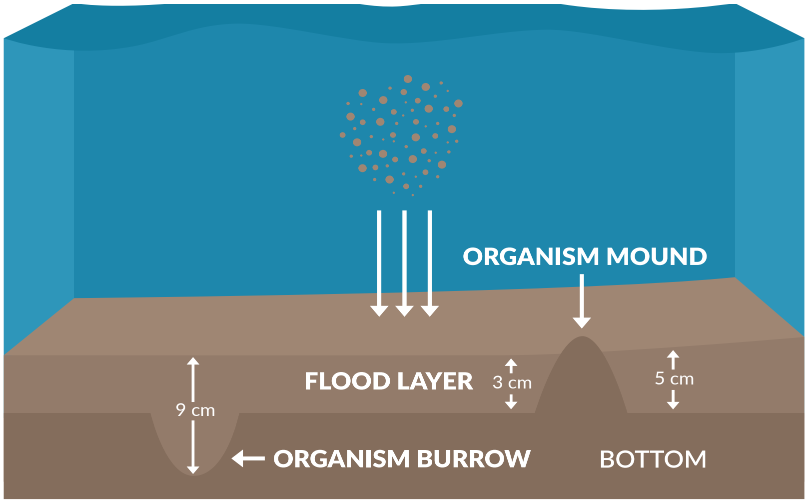
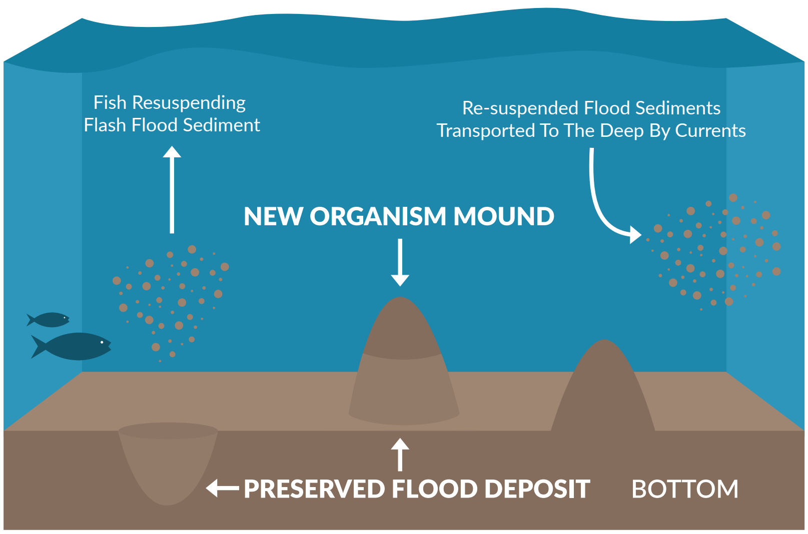


***Figure 3**. Diagram depicting tracer movement in ‘surface transplants’ compared to ‘deep transplants’.*

The results from these experiments are important because they highlight the undeniable role that biological activities play in shaping the seafloor. For future work, we need to zoom in closer, and focus on particularly abundant biological features within the seabed to learn more about how much sediment the organisms creating them can move. The knowledge we have gained



A. Initial variability in thickness of flashflood layer depending on local seafloor relief.



B. One year later - Local variability in flashflood preservation and removal from biological activities.

Figure 4. *Conceptual representation of flashflood deposit preservation and the effects of biological activities.*

from this study will certainly be useful to more accurately interpret what we see within the sediment record. This is especially true for marine environments with little sedimentation and an abundance of benthic organisms.

These field experiments have opened my eyes to the complex processes that occur in the seafloor. There is messiness, diversity, so much unknown, and as a scientist my job is to try to best interpret the system with the information I have. As the results come in, they continue to challenge me in thinking about this environment unbiasedly, and I must trust them to reveal the tale I want to tell.

THIS RESEARCH WAS FUNDED BY THE SCHULICH FOUNDATION AND THE NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL (NSERC)

Alysse Mathalon

Growing up in Toronto, Ontario, Alysse got her first taste of the ocean while visiting her grandparents in Florida throughout her childhood. She decided to study marine biology for her undergraduate degree at Dalhousie University, and soon after beginning, she never looked back. She was fascinated by the profound traits animals evolved to survive in the harsh ocean environment, and developed a passion for improving situations where human activities were negatively impacting marine life. She graduated with her Bachelor of Science with combined honors in marine biology and oceanography, and surveyed the presence of microplastics in the intertidal ecosystem of Halifax, NS for her honors research project, supervised by Dr. Paul Hill. Alysse went on to do her Master of Science at Dalhousie, and carried out her research in Eilat, Israel, through a collaboration funded by the Schulich Foundation. Again, Dr. Paul Hill supervised her project along with two Israeli oceanographers. Next up, Alysse is interested in focusing her efforts on integrating relevant science into marine management plans, and in contributing to improving the state of the ocean, so the amazing life it holds can persist.

Tracking the Work of the Ocean's Gardeners

Stable isotopes reveal microbial nitrogen transformations

Sebastian Haas

Microbes, the gardeners of the sea

Besides sunlight and water, nitrogen is what makes green things grow: it is the main fertilizing nutrient for plants on land and phytoplankton or algae in the ocean. Nitrogen is also a very versatile element that naturally occurs in a multitude of different forms and chemical states. In the sea, phytoplankton would be hard-pressed to fulfill their vital ecological role of photosynthesizing if it were not for the supply of nitrogen by the action of microbes (bacteria and archaea). For example, one study suggested that a reduction of nutrient input would decrease photosynthetic production in the tropical ocean by 4-fold. Such a dramatic decline of photosynthesis in the surface ocean would have massive effects on the Earth's climate.

Microbes transform nitrogen compounds as part of their metabolism and thus directly affect the degree to which phytoplankton can produce oxygen (O_2) and take up carbon dioxide (CO_2) via photosynthesis. This has important implications for life on Earth, including humans. Of course, these microbes do not actually care about their role of providing or withholding nutrients from phytoplankton. They use inorganic nitrogen compounds such as nitrate or ammonium in a similar way as humans and animals breathe oxygen: as electron donors or electron acceptors for the redox reactions they use to gain energy (See Figure 1 for a simplified depiction of the marine nitrogen cycle). Redox reactions are processes where one compound gets reduced, which means it gains electrons from another compound which is consequently oxidized. These reactions yield the energy that the microbes use.

There is an incredible diversity of microbes that have evolved an appetite for nitrogen compounds. One group called ammonium oxidizers, for example, turns ammonium

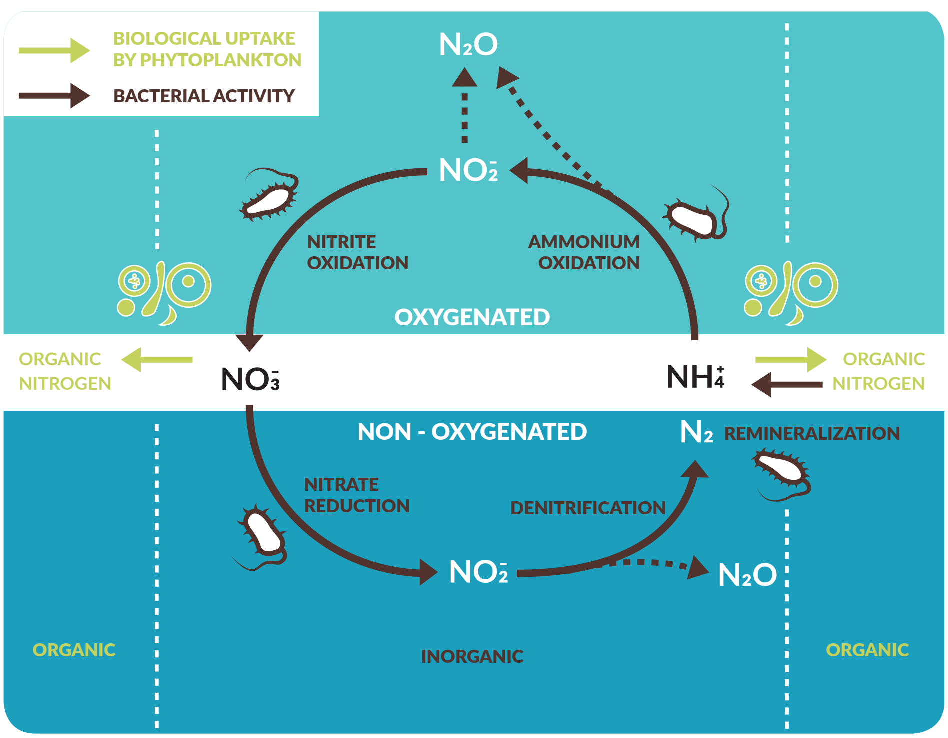


Figure 1. *A simplified scheme of the marine nitrogen cycle showing the main transformations occurring in oxygenated and non-oxygenated zones. Solid arrows represent main processes; dashed arrows by-products.*

(NH_4^+) into nitrite (NO_2^-) while nitrite oxidizers turn the nitrite into nitrate (NO_3^-). The combination of these two processes is called nitrification. These reactions provide the microbes with energy to uptake carbon dioxide (“chemosynthesis”), but only if there is oxygen around. Other microbes supply the ammonium by breaking down organic matter, independent of oxygen availability. Yet another group of microbes, so-called denitrifiers, can remove these oxidized forms of nitrogen by reducing nitrate or nitrite to dinitrogen (N_2), which only few microbes can use through a very energy-intensive reaction. Unlike nitrification, denitrification is only possible in the absence of oxygen. There is a large set of similar processes we know, most of them executed by microbes, which may co-occur and work in variable ways to transform different nitrogen species into others.

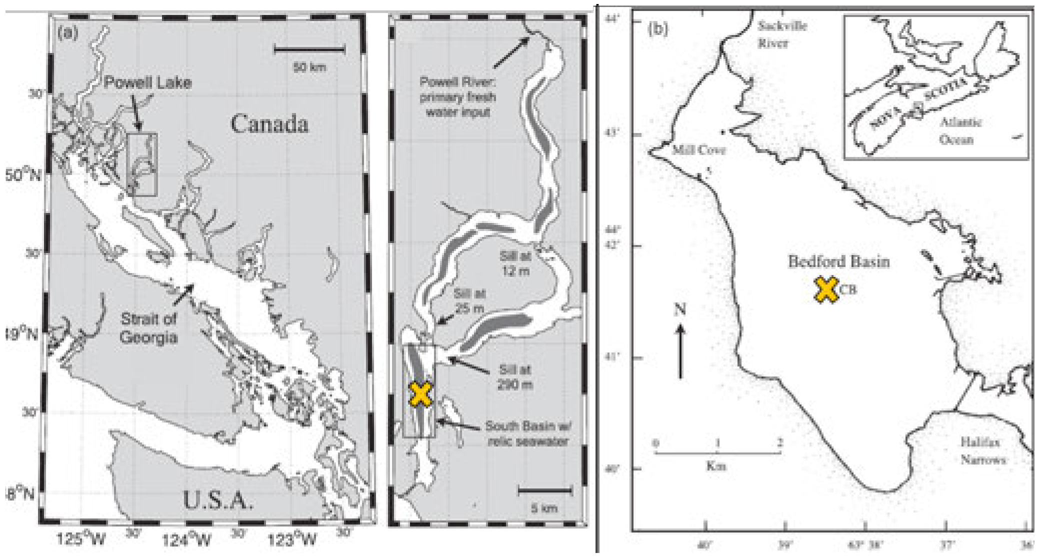


Figure 2. Maps of Powell Lake (left) and Bedford Basin (right) with the approximate sampling sites marked by yellow crosses. Credit: Scheifele and collaborators (2014, Marine Chemistry), Punshon and Moore (2004, Journal of Physical Oceanography).

Breathless gardening: what happens if the microbes don’t have oxygen?

The interactions of these microbial processes become especially interesting (read: *complicated*) in places where oxygen is limited or absent. In some areas of the ocean, zones of low oxygen content are found in the water column. These are called oxygen deficient zones and one of their characteristics is the occurrence of oxygen-dependent and -independent microbial processes very close to each other. This situation often presents itself in nutrient-rich waters such as near the coasts of Peru or Namibia. Large amounts of nutrients enhance production of organic carbon by phytoplankton, which in turn causes high oxygen-utilization (respiration) by microbes using this organic carbon.

The low oxygen content of the water poses threats not only to local ecosystems and fisheries but also to global climate, since emissions of nitrous oxide (N_2O), a very potent greenhouse gas, are unusually high in these zones. Nitrous oxide is produced as a by-product in both ammonium oxidation and denitrification, which can both occur in water columns where oxygenated and non-oxygenated waters meet. (Figure 1)

With global warming, oxygen deficient zones have been predicted to expand - one reason for this being that oxygen dissolves more readily in cooler water. The resulting increases in greenhouse gas emissions, surface nutrient supply and microbial production of toxic chemicals, such as hydrogen sulfide, will have an increasingly profound impact on human social and economic welfare. The effects are anticipated to be particularly devastating given that most oxygen deficient zones coincide with rich fishing grounds.

Stable isotopes in coastal basins: tools to trace microbial activity in ‘natural laboratories’

The aim of my research project is to better understand how environmental factors, such as oxygen concentration, salinity or physical mixing, affect the occurrence and rates of processes in the nitrogen cycle. For this purpose, I use coastal basins as natural laboratories to study nitrogen cycle processes occurring on a gradient from oxygenated to completely oxygen-depleted water. Compared to open ocean oxygen deficient zones, coastal basins are well-constrained entities with clear boundaries that are often easier to reach and study in more detail.

One of my two study sites is Powell Lake, a lake on the Canadian West Coast (Figure 2a). It has a highly stratified (experiences very little mixing), 350 metres deep water column. The lake had been a marine fjord until the end of the last ice age. The retreating mass of the glaciers led to an upward lift of the land mass around Powell Lake, thus separating it from the sea. Despite being isolated from the ocean for approximately 10 000 years, ancient seawater remains trapped at the bottom of the lake. Over time, a lighter freshwater layer established on its surface, creating a steep salinity increase and oxygen decrease from surface to bottom. Below 130 metres, the water is deprived of oxygen due to microbial respiration of organic material and salinity slowly increases with depth. This presents comparable (has oxygen interfaces), yet different (constrained space versus open ocean, freshwater meeting ancient seawater,…) conditions from oxygen deficient zones, which potentially allows for identification of factors influencing the processes of interest.

Contrastingly, my second study site, Bedford Basin on the Canadian Atlantic coast (Figure 2b), is a marine fjord with dissolved oxygen concentrations varying throughout the year. Continuous mixing of the water in late winter and spring results in oxygen addition to the entire water column. In the deeper parts of the water column, the added oxygen is then slowly used up by biological processes over summer and fall when the water column is stratified. This creates a temporal oxygen gradient which often leads to a short period of low-oxygen conditions at the end of the year. Weekly sampling for nitrogen isotope measurements allows us to observe the effect that oxygen and other environmental factors have on nitrogen cycling in Bedford Basin.

From small boats, we take water samples from these basins, which are then processed and analyzed in the laboratory for the concentration of nitrogen compounds and their stable isotope composition. The stable isotope composition can reveal the underlying microbial processes, such as the ones introduced above. This is because nitrogen cycling microbes happen to be picky! There are two stable (non-decaying or non-radioactive) isotopes of nitrogen, ^{14}N and ^{15}N. Most processes, including those employed by nitrogen cycling bacteria, proceed more readily if a compound contains ^{14}N rather than ^{15}N. Hence microbes will often use more ^{14}N than ^{15}N compounds if they have a choice. We exploit this peculiarity by measuring the ratio of ^{15}N over ^{14}N (expressed as $\delta^{15}N$) in a given pool of nitrogen compounds. If microbes are using or producing a nitrogen compound in a given parcel of water, they will leave behind a predictable mark on the $^{15}N/^{14}N$ ratio of this compound's pool, meaning the ratio will change in a predictable manner over time or water depth. Hence, using mass spectrometry (which separates and counts the two isotopes by mass using a strong magnet) to measure this isotope ratio in nitrate, nitrite and ammonium allows us to trace the microbial processes that underlie changes in the pools of these inorganic nitrogen compounds.

First results from...

...Powell Lake, containing ancient seawater free of oxygen

In the summer of 2016 we took water samples from many depths throughout the permanently stratified (unmixed) water column of Powell Lake. Preliminary analyses show large accumulations of ammonium, reduced inorganic nitrogen, in the non-oxygenated deep water, which is evidently the product of microbial degradation of organic material (Figure 3). Unlike in Bedford Basin (see below), where dissolved oxygen in the water column allows for the oxidation of ammonium into nitrite and nitrate, only oxygen-independent processes could potentially remove part of the ammonium. As has been previously observed in similar environments, nitrous oxide is produced at the bottom of the oxygenated layer, and consumed at the top of the oxygen-free layer. In Powell Lake, nitrous oxide showed additional, smaller maxima in deeper parts of the oxygen-free zone. Nitrogen stable isotope analysis as well as molecular analysis (bacterial and archaeal DNA), are likely to reveal an unusual interaction of processes that are transforming nitrogen compounds in this extreme environment.

...Bedford Basin, where things get a little more turbulent

Our weekly time series of nitrogen stable isotope composition in the deep water (60 metres) of Bedford Basin, Nova Scotia, revealed how during periods of water column stratification in summer and fall, a 'nitrification cascade' developed: nitrogen was transformed from ammonium via nitrite into nitrate (Figure 4). As expected, $\delta^{15}N$ values of these compounds changed due to microbial discrimination between the stable isotopes. While we observed this nitrification cascade during each of the three years of observation, differences between the years were evident. The large peak in nitrite concentration in 2015 was not visible in the other two years. Yet, the isotopes of nitrite behaved similarly

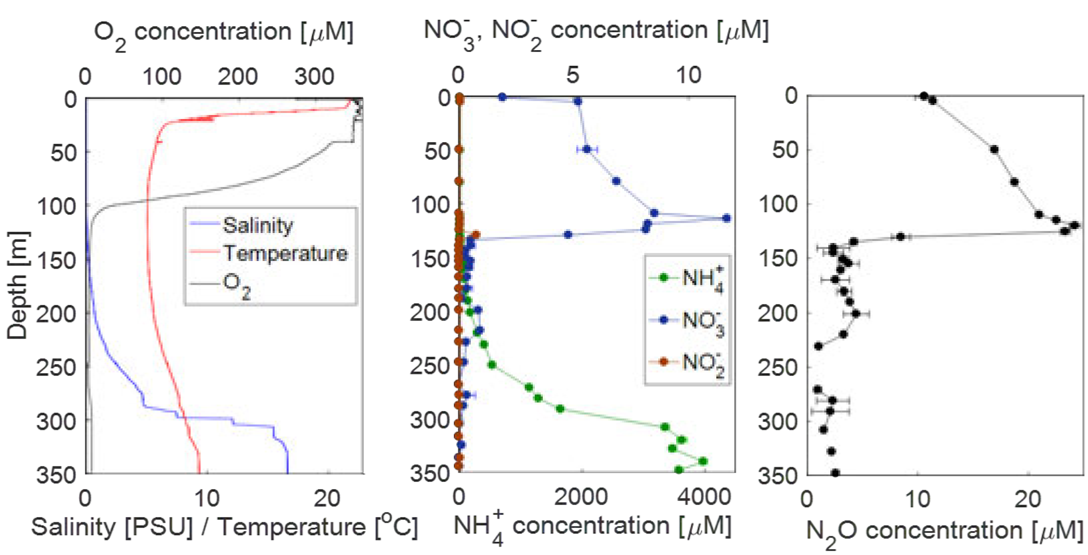


***Figure 3.** Vertical profiles of, salinity, temperature, oxygen, nutrients (ammonium, nitrate, nitrite) and nitrous oxide in Powell Lake, Southern Basin, in August 2016. Concentration units are micromoles per litre (µM) and Practical Salinity Unit (PSU).*

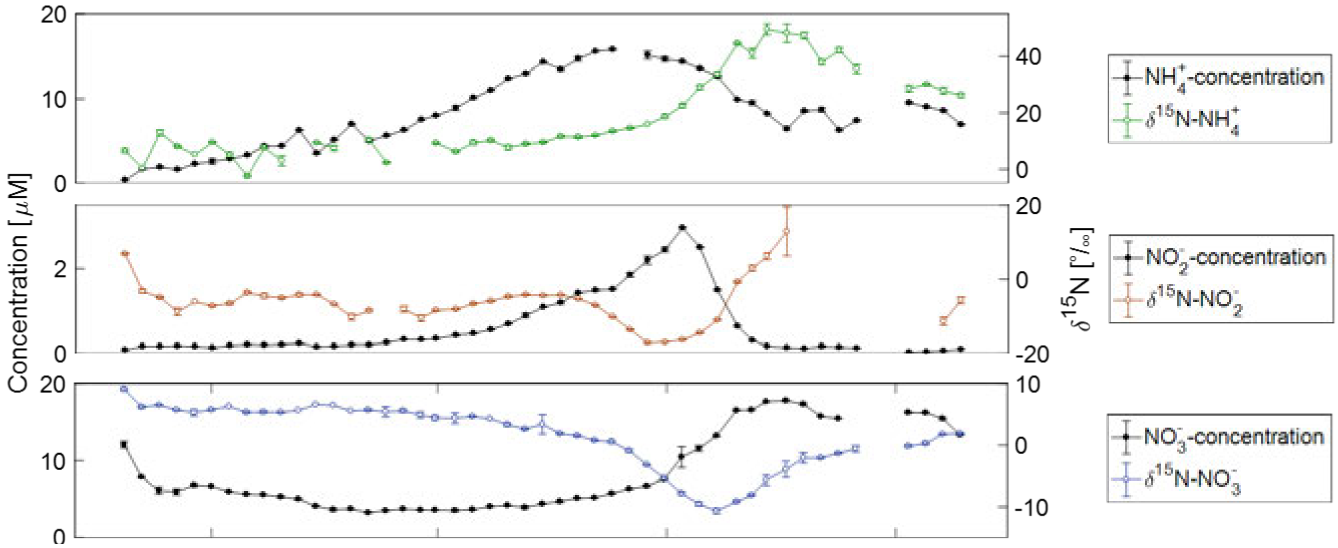


Figure 4. *The nitrification cascade at 60 metres depth in Bedford Basin in 2015, when ammonium was oxidized to nitrate via nitrite. Changes in stable isotope composition of the different compounds (green, red and blue) reflect microbial processes underlying concentration changes. Concentration units are μM.*

throughout the study period, which indicated that ammonium and nitrite oxidizing microbes were active in all three years. The differences in nitrite accumulation may be due to changes in water temperature, the presence of different types of microbes or the timing of additional short water column mixing events during summer, which in 2014 and 2016 may have flushed out most of the nitrite that accumulated in the absence of summerly mixing events in 2015. Closer analysis of this time series dataset may reveal factors that enhance or suppress ammonium and nitrite oxidation and their interaction with other processes.

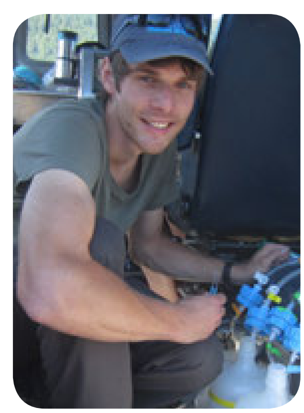
What do we hope to learn about the gardeners?

The Bedford Basin time series allows us to observe the impact of environmental factors on the nitrogen cycle in a dynamic coastal system with seasonal changes. Comparison with Powell Lake, which has not undergone mixing for several millennia, is expected to yield knowledge about how physical mixing and the resulting differences in water column oxygenation affect nitrogen cycling processes qualitatively (which processes?) and quantitatively (process rates, greenhouse gas emissions). Besides illuminating the differences in the nitrogen cycle between types of coastal basins, these results may also be compared to other studies in open ocean oxygen deficient zones which might help to explain the reasons for differences we see between these systems.

THIS RESEARCH WAS FUNDED BY THE CANADA EXCELLENCE RESEARCH CHAIRS PROGRAM (CERC. OCEAN), AN IZAAK WALTON KILLAM PREDOCTORAL SCHOLARSHIP AND A NOVA SCOTIA GRADUATE SCHOLARSHIP (NSGS).

Sebastian Haas

Sebastian grew up in rural Bavaria, Germany, and has always been fascinated by nature and the functioning of ecosystems. A class on environmental microbiology during his undergraduate studies at the University of Bayreuth made him realize that microbes do even more fascinating things than plants and animals. He also had to learn that the things that most interested him take place on a chemical as much as on a biological level and he since has come to describe himself as a biogeochemist. The desire to study the way microbes shape the environment led him away from his beloved mountains to the shores of the North Sea. His MSc at the Max-Planck Institute for Marine Microbiology in Bremen was on the lifestyle of peculiar bugs in a Bahamian underwater cave. After a detour through Asia, he ended up at Dalhousie to study the nitrogen cycle in Canadian waters and to explore the beautiful nature of Nova Scotia in his free time.



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.

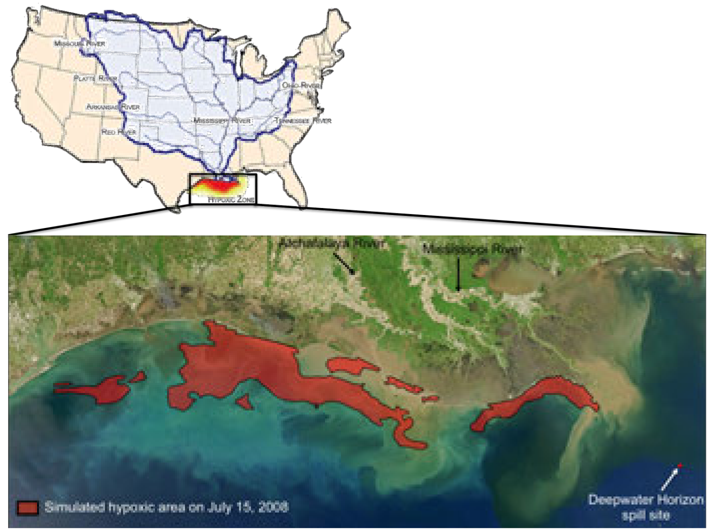


Figure1. *Satellite image (MODIS sensor) showing the plumes from the Mississippi and Atchafalaya Rivers. Red area represents approximate size and location of hypoxic zone from model simulation. Left upper corner: A map of the Mississippi River drainage basin (light purple block, picture from US EPA).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

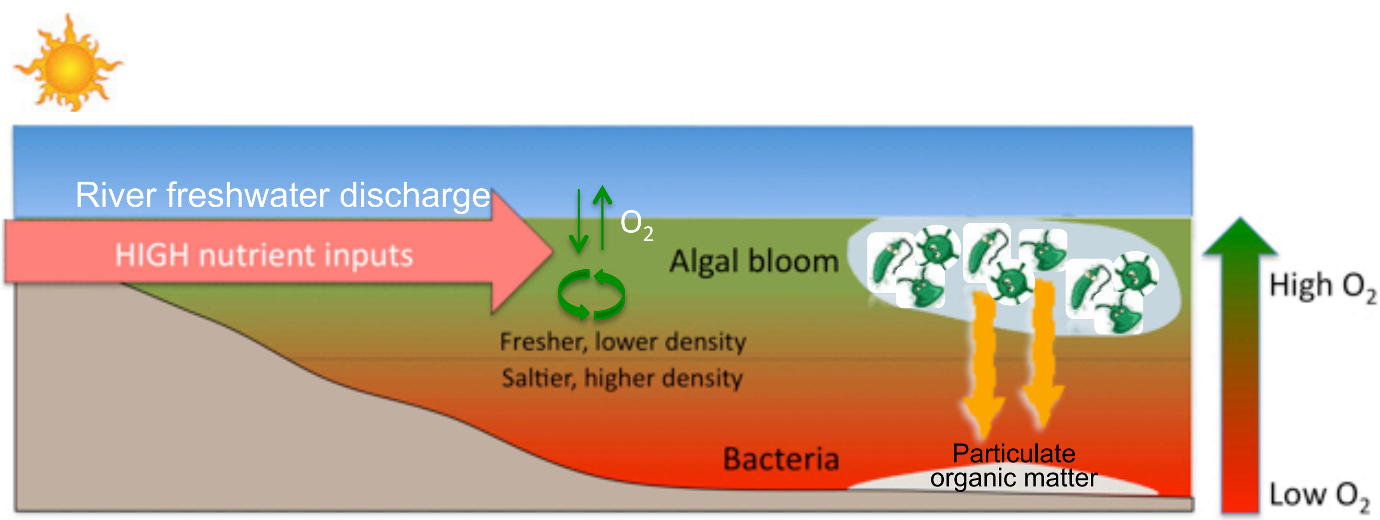


Figure 2. *Schematic of low-oxygen dead zone formation (adapted from http://www.vims.edu/).*

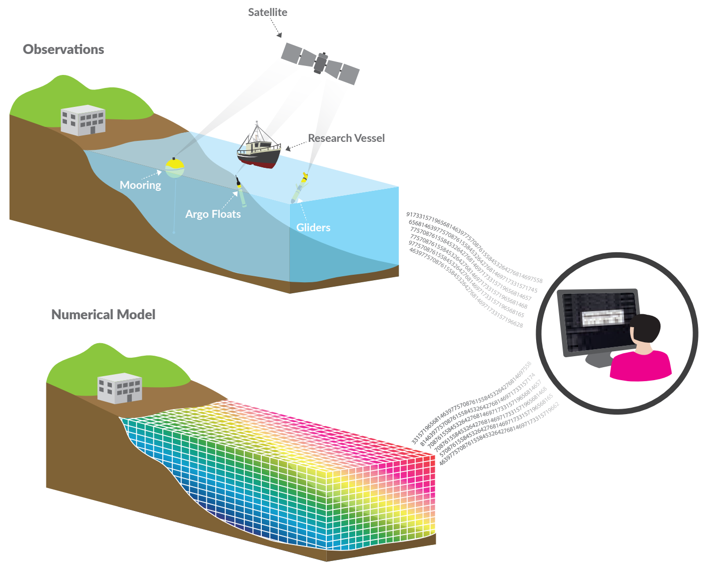
Further off the coast, the deeper waters in the GOM may be less impacted by the farm runoff, but are increasingly stressed by the intensive oil and gas exploration in the deep GOM. Most recently, the explosion and sinking of the offshore drilling rig Deepwater Horizon in the GOM in April 2010 created 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,

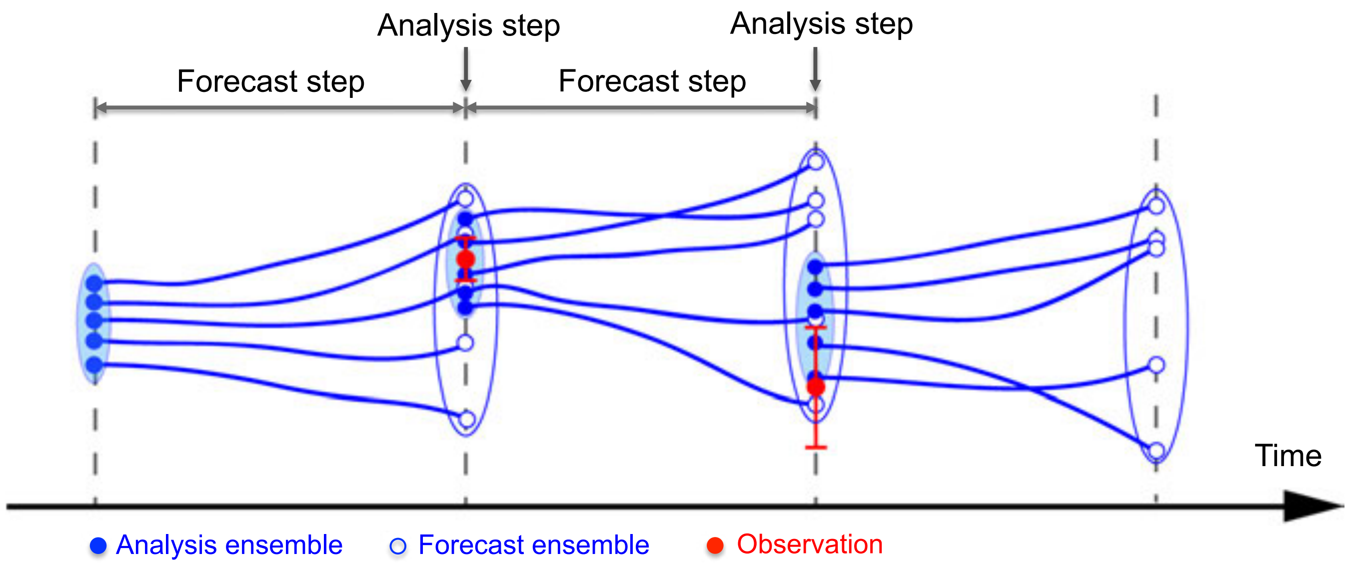


***Figure 3.** Schematic diagram of the Ensemble Kalman Filter procedure. During the forecast step, an ensemble of model simulations (blue) is integrated forward in time until observations are available. The forecast ensemble (empty dots) provides an estimate of the model uncertainty (represented by 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.

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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.

Playing with Mud

Investigating the ecological value of coastal sediments

Francisco Bravo-Avendano

While many of us have fond childhood memories of playing with mud or building sandcastles, some of us keep doing it as adults! Mud is not only a fun material to play with, but it is also essential to the environment that surrounds us. Soils, freshwater sediments and marine sediments are the substrates of the largest ecosystems on Earth. Oceans cover around 70% of the planet surface and most of the seabed is covered by sediments. Marine coastal sediments and associated communities (known as the benthos) provide benefits to humans such as food provision, pollution control, and coastal protection, among others. These benefits, also known as *ecosystem services*, are provided through ecological functions and processes such as habitat provision to flora and fauna, nutrient cycling, burial of solids and dissolved compounds, and sediment stabilization.

Compared to more stable deep-sea environments, coastal areas are characterized by changing temperature, chemistry, and hydrodynamic conditions. As a result, benthic processes such as nutrient cycling vary significantly in time, as well as across different sedimentary environments (for example: estuaries, deltas, beaches, tidal flats, among others). Understanding the scales of variability in benthic processes provides valuable insight into the functioning of marine coastal ecosystems and the ecosystem services of coastal sediments.

The science of mud play

Under the supervision of Dr. Jon Grant at Dalhousie University, my research aims to study the variability and contribution of soft-sediment communities to carbon and nutrient cycling in coastal areas. Additionally, I am also interested in investigating the effects of fish farm organic wastes on soft-sediment communities. To achieve these objectives, I combine three different research tools: field/laboratory experiments, benthic habitat mapping, and numerical models. These research tools provide a means to study benthic processes at various spatial scales, from the local effects of organic enrichment of sediments underlying a fish farm to large-scale processes occurring throughout an entire bay.

Field and laboratory experiments

Most of my fieldwork is focused on measuring benthic metabolic rates, which refers to the rates of processing of matter and energy by benthic organisms. I make this measurement by using benthic incubations, which involve isolating an area of sediment with an acrylic-capped core so that the exchange of gases (such as oxygen) and nutrients (such as nitrate and phosphate) between the sediments and the overlying water can be measured. The exchange of substances is associated with the metabolic activity of organisms living within the sediments, and may vary significantly across different sediment types, from muddy to sandy sediments. Some incubations are carried out on site while others are conducted in the lab (Figure 1). Sediment samples for

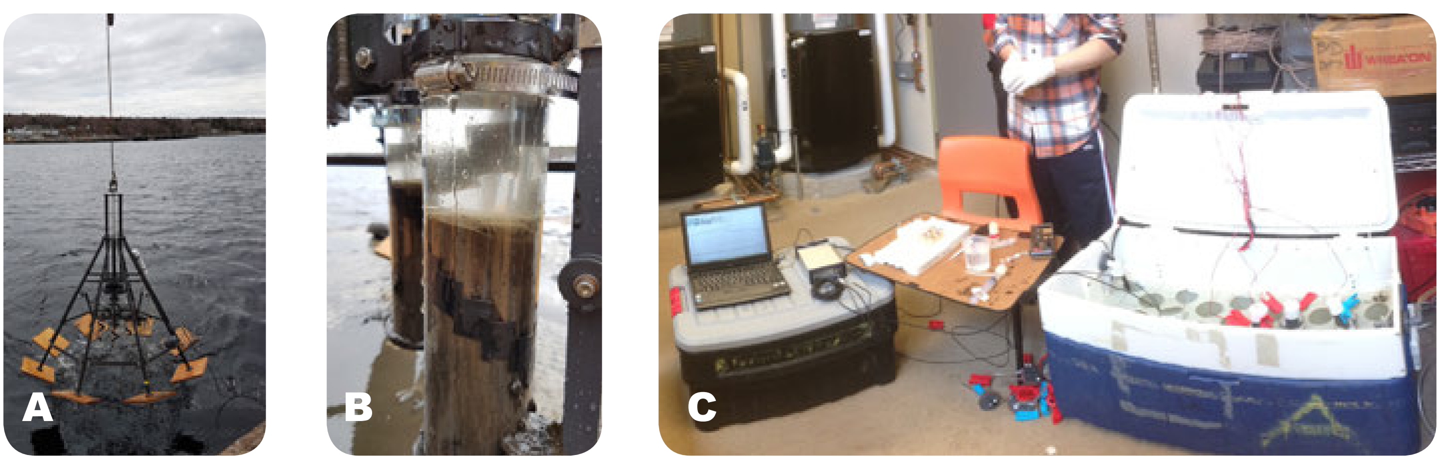

***Figure 1. A.** Multicorer designed to retrieve sediment and water samples. **B.** A sediment core collected with the multicorer. **C.** Laboratory incubations of sediment cores for nitrogen gas measurements.*

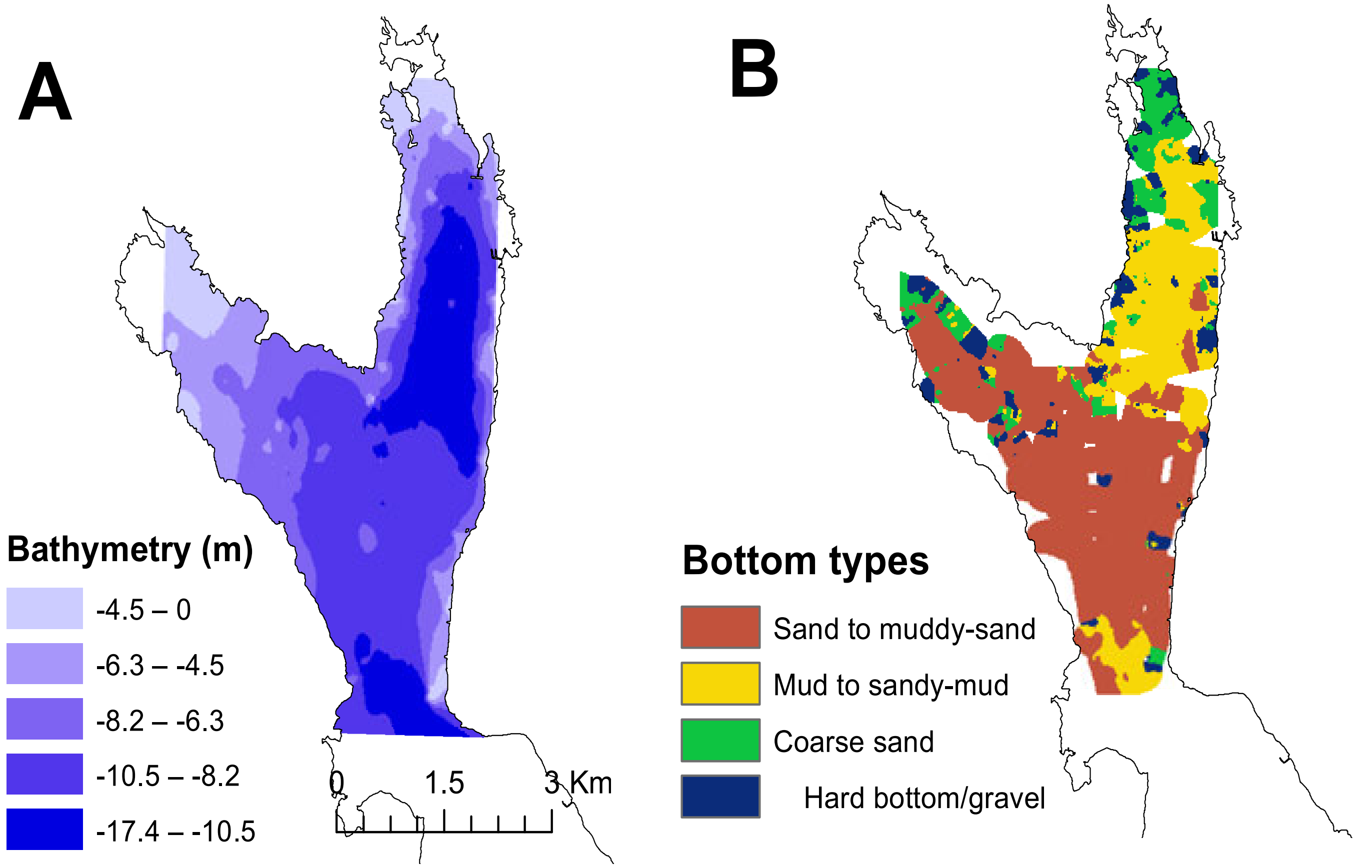

Figure 2. *Benthic habitat mapping of Shelburne Bay, NS, Canada.* ***A.*** *Bathymetry.* ***B.*** *Organic matter content in surface sediments.*

laboratory incubations are either collected by SCUBA divers or with equipment designed to collect undisturbed samples (an example is the multicorer in Figure 1A). The purpose of these laboratory incubations is to provide controlled environmental conditions (that is, light, temperature, and salinity) so we can accurately measure benthic processes without potentially confounding factors (see Figure 1C). All of our samples were collected on the South Shore of Nova Scotia, Canada.

Benthic mapping

Benthic habitat mapping is an essential tool for coastal researchers because it reveals the spatial distribution of physical and biological variables, which can be important for both ecological studies and management purposes. For example, Figure 2 shows depth (A), and sediment type (B) of a small and active bay in Southern Nova Scotia, Canada. These maps were produced using a combination of remote (acoustic surveys; using sound to look at the seafloor) and direct (grabs and sediment cores) sampling methods. I used this information to guide the site selection for the benthic incubations and also as an input for numerical models developed to predict carbon and nutrient cycling in sediments in the entire bay.

Numerical models and budgets

Numerical models are computational codes used to capture or simulate the behavior of a particular system. Models encapsulate our understanding regarding natural phenomena and are useful in interpreting observations and cause-effect relationships. Discerning causes of natural phenomena is not always easy, especially when observations only show the net result of opposing benthic processes, such as in consumption-production, precipitation-dissolution, or oxidation-reduction processes. As predicting tools, numerical models allow us to interpolate and extrapolate processes in time and space, which is particularly relevant when the coverage of field measurements is limited, or the studied process is not directly measurable. More recently, numerical models, the performance of which is evaluated by comparing to field measurements, have also become valuable as environmental management tools supporting decision-making processes. For example, the balance between sources and sinks of nitrogen greatly defines the productivity and water quality of coastal bays. Therefore, information and predictions from numerical models on the cycling and fate of nitrogen is fundamental to our understanding of how the system will respond if this balance is perturbed.

When the game gets complicated

Despite careful control of experimental conditions, field and laboratory observations are often wildly variable and difficult to interpret – they just do not make sense. The variability observed may result from inherent natural variability in the environment or from measurement error. Distinguishing between both sources of variability is very important, but not always easy to do. In addition, complex interactions may be observed when multiple factors simultaneously control benthic activity. Some factors may inhibit a particular process, while others may favour it. For example, the degradation of organic matter in sediments depends simultaneously on the availability of oxygen required to oxidize (decompose) organic matter and on water temperature that may inhibit benthic activity at low values. Describing these underlying dynamics is crucial to the understanding of the driving forces of benthic processes and their contribution to matter and energy cycles in coastal oceans.

Serious games

As mentioned earlier, the benthos provides many benefits to the human population. However, human activities such as dredging, trawling, and pollution can seriously affect the biodiversity and functioning of the benthos. In my research, I have focused on the environmental effects of organic waste produced at fish farm sites, including feces and excess feed, and on the chemistry and biology of sediments underlying fish farm cages. Depending on depth and currents, fish farm waste discharged out into the ocean can accumulate on the sea-bed below the fish cage, be buried into sediments, or be dispersed to far away areas. The excessive deposition of organic material and its degradation can lead to anoxic conditions (lack of oxygen), the accumulation of toxic compounds such as sulfide, and the progressive loss of macrobenthic communities. This situation, known as eutrophication, is undesirable but difficult to avoid when the capacity of the benthos to degrade organic wastes is unknown.

I used numerical models to predict the fate of organic wastes produced at a fish farm including its dispersal in the water column and its deposition, resuspension, and degradation on the seabed. A schematic showing these processes is provided in Figure 3. The numerical model is composed of three modules representing a marine salmon farm, the surrounding water column, and the benthos. Once the model accurately simulates field measurements, it is used to predict the

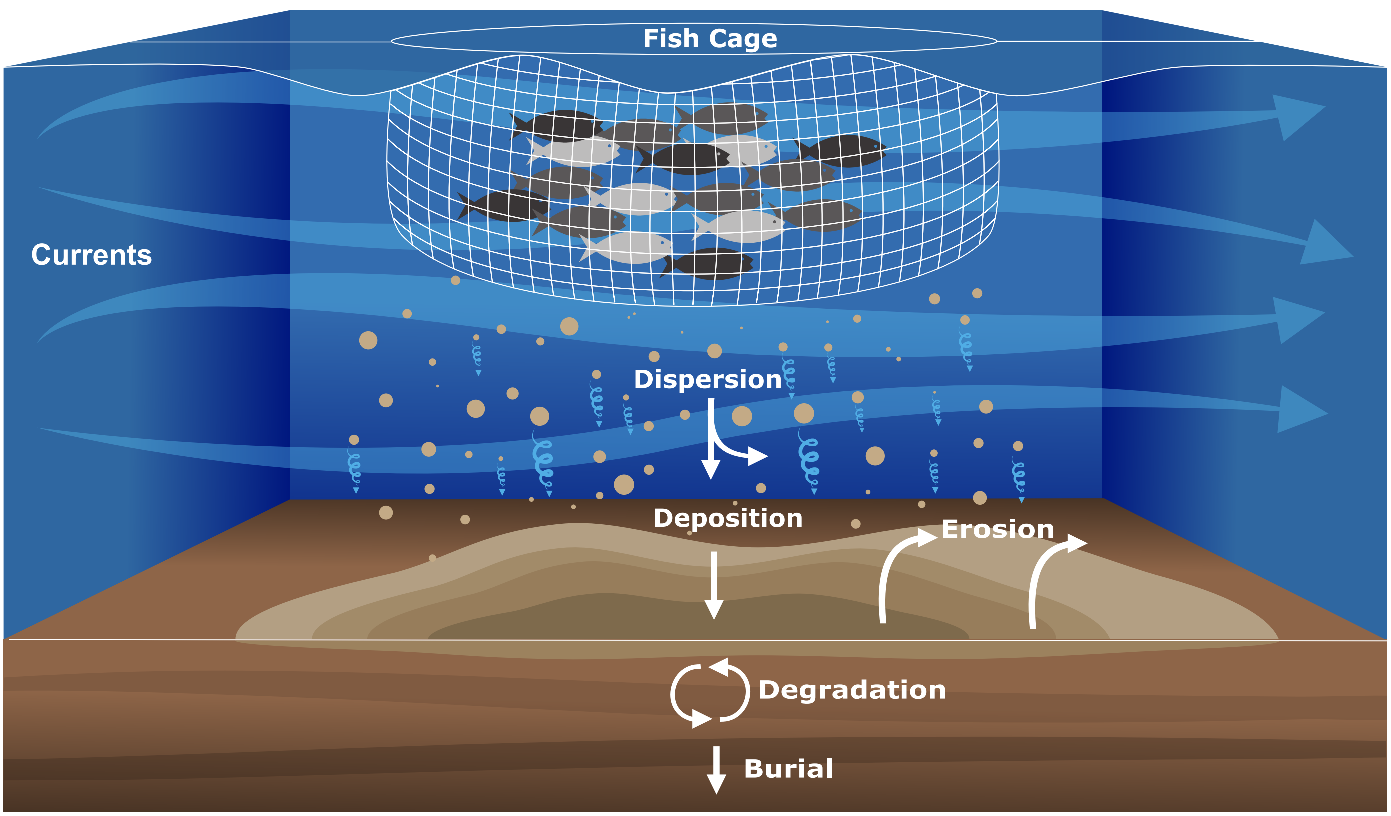

Figure 3. *Schematic of the fate of particulate organic wastes produced at the fish farm (lost feed and feces) and their discharge into the ocean. Depending on depth below the fish cage and currents, these wastes can accumulate at the sea-bed below the fish cage, be buried into sediments or dispersed to the far-field. The excessive accumulation of wastes at the sea-bed can lead to anoxic conditions and accumulation of toxic compounds affecting the abundance and biodiversity of benthic communities.*

organic loads that can be degraded in sediments without compromising environmental conditions and, per provincial regulations, fish farm operation.

Figure 4 shows an example where the suitability of fish farm operations is predicted based on oceanographic conditions of depth and mean current speed, the production of organic wastes, and their impact on sediment quality. Environmental performance of aquaculture operations is considered successful if sulfide concentration, a metabolic product of anaerobic degradation of organic matter (that is, in absence of oxygen), does not increase above toxic levels for benthic fauna. A precautionary area (in yellow) is defined as any combination of organic waste production and mean current speed leading to sulfide concentration between 1500 and 6000 micromolar (μM). These thresholds correspond to moderate and high toxicity for benthic fauna, respectively.

Outlook and perspectives

In my research, a suite of experimental, observational, and modeling tools were used to study benthic metabolism. The knowledge gained in measuring and modeling carbon and nutrient cycling in coastal sediments enabled me to characterize the environmental controls of benthic activity (such as carbon deposition), as well as the contribution of sediments to the cycling of nutrients in a coastal bay. Likewise, with the development of numerical models of aquaculture-environmental interactions, I was able to evaluate the relationship between fish farm production and the response of benthos to the deposition of organic waste associated with that production. The development of numerical models in support of sustainable aquaculture is particularly relevant for areas of rapid expansion of aquaculture operations, such as Canada.

Playing with mud is more than just fun. It is a great way to learn about the role that coastal and marine processes play in shaping sedimentary environments. Children and adults alike can always find a good excuse to play in the mud, so why not get down and dirty?

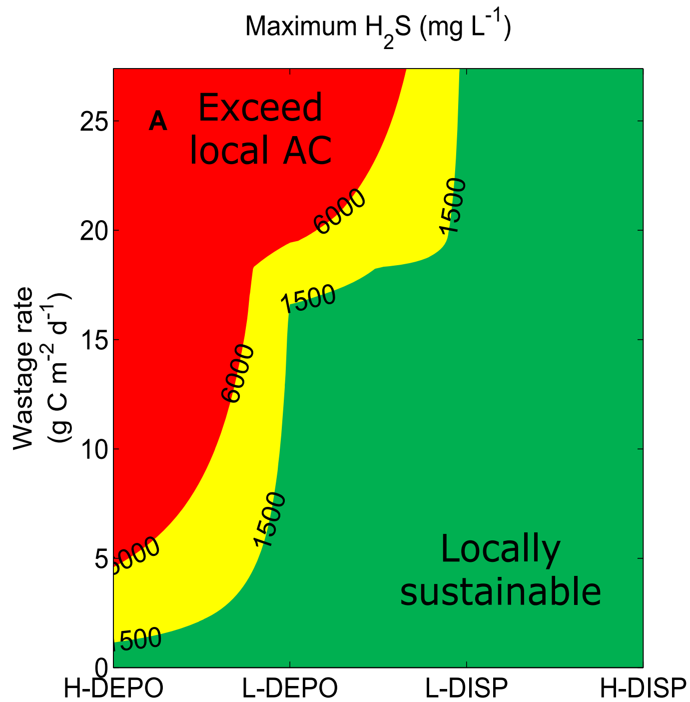

Figure 4. *Traffic light model predicting environmental sustainability of aquaculture operations based on hydrodynamic conditions, organic waste production, and benthic response.*

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Francisco Bravo-Avendano

Francisco is a marine biologist and recently obtained his Ph.D. in oceanography at Dalhousie University. Francisco's professional and research interests are focused on management, monitoring, and modeling of coastal zones and processes, including natural and socioeconomic dimensions. He has worked actively in consulting associated with innovation and entrepreneurship in small-scale fisheries, the evaluation of environmental interactions of industrial activities, and fisheries monitoring in the Southeast Pacific.
As a Ph.D. student, he focused on the modeling of coastal ecosystem services, the quantification of natural benefits that coastal oceans provide to people, and on aquaculture-environment interactions.
When not working (or playing with mud!), he enjoys spending time with his family and friends, playing sports, and discovering Nova Scotia.

Heading North: Following Carbon Dioxide to the Canadian Arctic

Investigating how upwelling alters the cycling of carbon in a changing climate

Jacoba Mol

Aboard the CCGS Amundsen

Very few people will ever get to see this. That's one of the main thoughts that goes through my head when I am standing on the deck of the Canadian Coast Guard Ship *Amundsen* (Figure 1) to sample water from the Arctic Ocean at 3 A.M. with the sun still shining bright. I have been lucky enough to take four trips on the Amundsen to do research in the Canadian North. On each of these journeys, the landscapes, animals, people, and sights have contributed to experiences far beyond what I ever thought I would do or see in my lifetime. Over these four trips, I have spent a total of 197 days on the Amundsen. Throughout each of these days I have marveled at the beauty of the Canadian Arctic and worked to gain a greater understanding of the ocean and environment around me.

Figure 1. *Canadian Coast Guard Ship Amundsen. Photo Credit: Dave Babb*

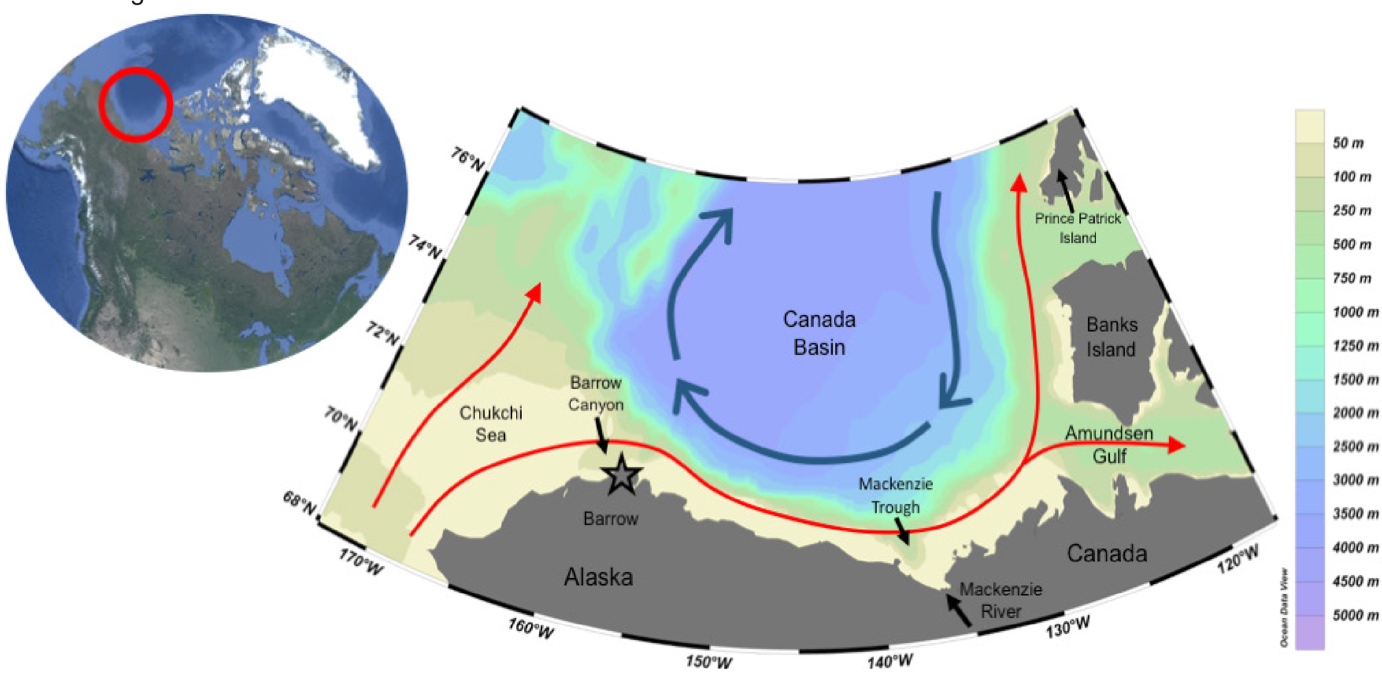


Figure 2. *Ocean depth and sub-surface circulation in the Beaufort Sea (location indicated by the red circle on the map). Red arrows indicate the sub-surface flow of Pacific water entering through Bering Strait and forming the shelf-break jet. Blue arrows indicate the clockwise flow of the Beaufort Gyre. Black arrows indicate river inflow and topographic features.*

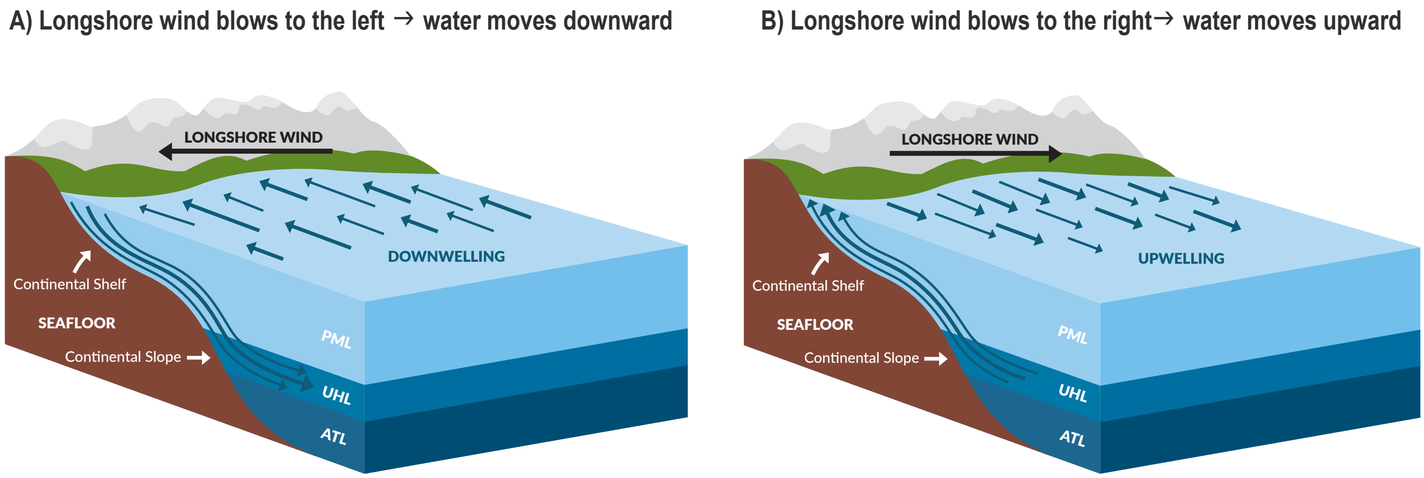


Figure 3. *Wind-induced downwelling and upwelling on the Mackenzie Shelf. Water mass layers are indicated, with the polar mixed layer (PML) on top, the upper halocline layer (UHL) in the middle, and the Atlantic layer (ATL) on the bottom. Alongshore wind causes surface water movement to the right of the wind direction. When wind comes from the west alongshore, water at the surface moves toward shore, and creates downwelling of water at depth. When wind comes from the east alongshore, this causes off-shore water movement at the surface and upwelling of deep water.*

The Amundsen is a unique and valuable platform for science. Here, forty scientists from across Canada and around the world gather every summer, all with different scientific interests, but sharing one common goal: to better understand the Arctic. Doing research in the Arctic is not always an easy task, but it is critically important. Once you have travelled to this distant place, you gain a sense of the urgency and need to understand this fragile ecosystem. This is an area that is experiencing change at a faster rate than anywhere else in the world. Changes in temperature, sea-ice concentration, and river input, among others, are altering the ecosystems and environment in ways that are hard to predict. The interconnectivity of environmental factors within this remote region is critically important to understand, as changes in the Arctic will lead to changes throughout the rest of the world.

To the Beaufort Sea: water masses and movement

The water of the Arctic Ocean is divided into well-defined layers. The top layer, called the polar mixed layer, is a combination of river input, sea-ice melt, and Pacific-origin water that has entered through the Bering Strait. Pacific-origin water is below this surface layer, at approximately 100 metres (m) depth; this is also the location of the temperature minimum. Water temperatures then increase in the layer below, where the water is sourced from the Atlantic Ocean. The Beaufort Sea lies over the deep Canada Basin, in the middle of which is the Beaufort Gyre, spinning in a clockwise direction (Figure 2). Along the shelf-break of the Beaufort Shelf, which is the transition area between the shallow shelf and the deep basin, a narrow current (15-20 kilometres wide), known as the shelf-break jet, flows from the Bering Strait east towards the Canadian Archipelago (red line in Figure 2).

Along the edge of the Beaufort Sea, on the Beaufort Shelf, is a section called the Mackenzie Shelf. This piece of continental shelf, the shallow near-shore ocean region that is part of the continental crust, is located where the land of the Yukon and the western Northwest Territories reach the ocean (Figure 2). The Mackenzie River, the second largest river in Canada, contributes freshwater to the ocean over the shelf. On the Mackenzie Shelf, the most important driver of change in water circulation is wind forcing. The direction of the shelf-break jet can be altered by storms over the Beaufort Sea as the wind direction changes. If the shelf-break jet is accelerated by winds from the southwest, a process called downwelling can occur as water at the surface moves to the right of the wind motion (that is, toward land) and builds up, forcing water at depth to move into the deep basin (Figure 3a). If winds are instead coming from the northeast, the jet can reverse its direction of normal flow, while surface water moves offshore to the right of the wind direction. This reversal of flow creates upwelling, meaning water at the surface is pushed away from the shelf towards the central basin, and water from below the surface layer is moved from the basin onto the shelf (Figure 3b). Upwelling is an important process in the coastal ocean because it brings water high in nutrients to the surface where primary production can take place. The Mackenzie Shelf in particular is an area that is known to have strong and active upwelling, bringing Pacific-origin water that is high in nutrients and inorganic carbon onto the shelf.

Carbon dioxide on the Mackenzie Shelf

The burning of fossil fuels has led to an increase in the concentration of carbon dioxide (CO_2) in the atmosphere, and consequently higher levels in the oceans as CO_2 is taken up by the surface layer. The ocean exchanges CO_2 with the atmosphere, in some regions taking up CO_2 from the atmosphere and in other regions putting CO_2 into the atmosphere. The direction of the exchange is dictated by the partial pressure of CO_2 (pCO_2; a relative measure of gas concentration) in both mediums, with the gas moving from regions of high to low concentrations. When CO_2 enters the ocean, it dissolves and forms carbonic acid (H_2CO_3), which then dissociates to form bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. These dissolved forms of CO_2 are collectively called total dissolved inorganic carbon (DIC). Phytoplankton in the ocean act just as plants on land do, taking up CO_2 and using it for photosynthesis to produce oxygen (O_2) and organic matter. Respiration occurs when this organic matter sinks and is broken down back into dissolved CO_2. This sinking of organic matter results in a greater buildup of DIC below the surface layer in the Pacific-origin layer. When storms occur that produce upwelling, this high DIC water can be brought onto the shelf, and possibly to the surface, having implications for the exchange of CO_2 between the ocean and the atmosphere, and carbon cycling on the shelf.

Tricks of the (carbon) trade

To investigate how and when DIC moves between the basin and shelf regions, I took water measurements on the Mackenzie Shelf in August and September of 2014. Water is sampled from a rosette, an instrument with 24 large bottles and various sensors to measure parameters such as tempera-

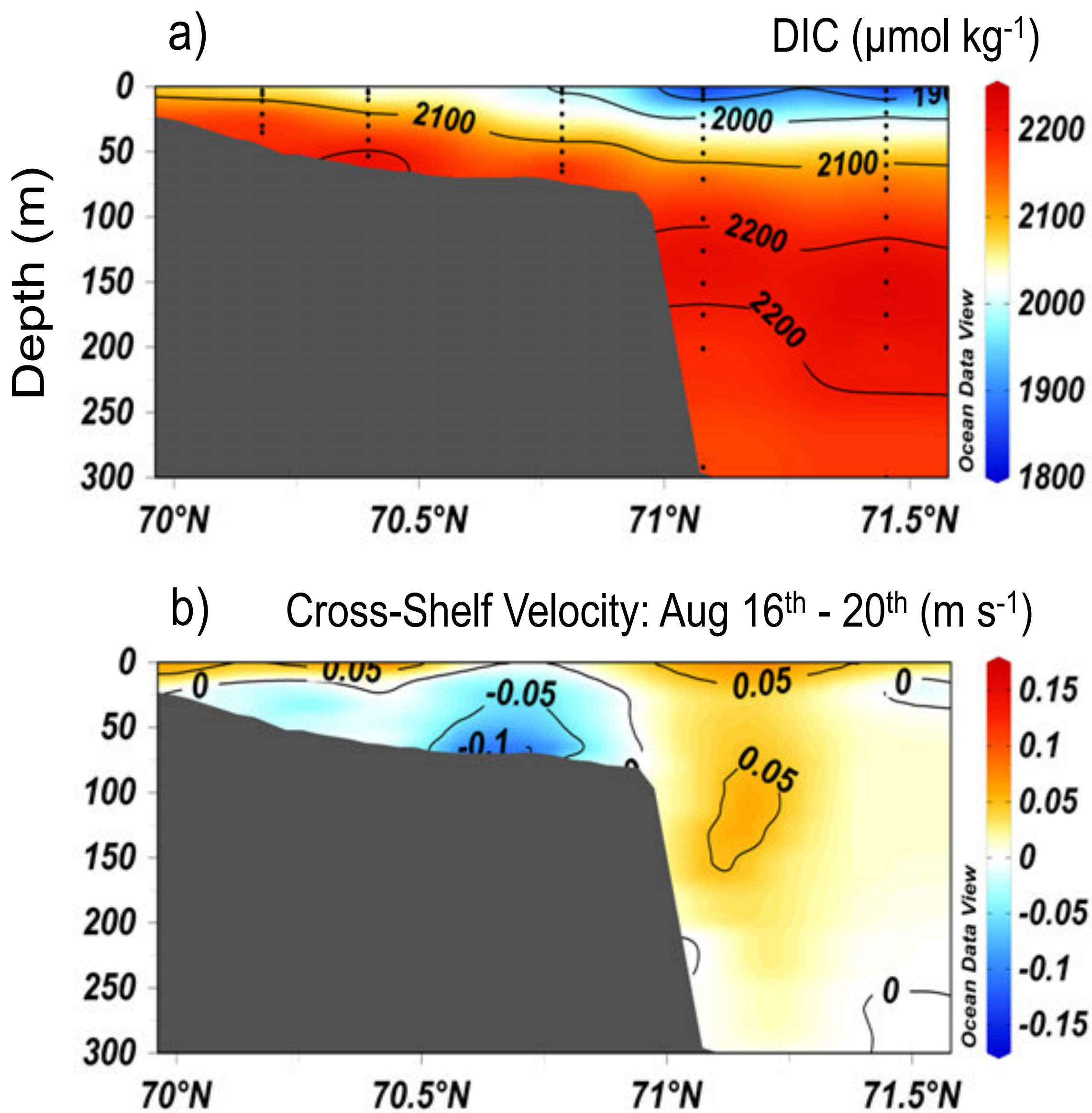


Figure 4. a) Dissolved inorganic carbon (DIC) and b) cross-shelf velocity shown on a cross section of the Mackenzie Shelf. The black dots show samples taken for DIC and the colour indicated the concentration. The cross-shelf velocity is taken from a model; colour indicates velocity with negative (blue) values going toward the shore and positive (red) values going off the shelf toward the deep basin.

ture, depth, salinity, dissolved oxygen and light. The rosette is put over the side of the ship on a cable and lowered close to the bottom of the ocean. It is then pulled back through the water to the surface and onto the ship, stopping at certain depths so that bottles can be triggered to collect water. I then take this water back to the lab in small glass bottles and measure the amount of CO_2 in each sample. These samples give me an idea of the spatial distribution of DIC throughout the water column and over the entire study region, from on the shelf to out past the shelf-break (Figure 4a).

The other main tool that I use to investigate upwelling and carbon cycling is the output of water velocity from an ocean model. This model recreates five-day averages of the circulation in the Beaufort Sea, giving an idea of where and how fast water is moving through the entire water column. This simulation of the water velocity can be used to look at when upwelling, or alternatively downwelling, is taking place over the continental shelves by looking at the cross-shelf velocity over the shelf (Figure 4b). Combining the discrete DIC measurements and the model, we can infer where carbon is being transported. Water property measurements are only taken once a year, providing a snapshot of the carbonate system over the shelf, while the model is run for the entire year. This limited sampling in hard to reach regions like the Beaufort Sea means that seasonal changes and alterations in the system are hard to constrain.

The Mackenzie Shelf, upwelling and increased pCO_2

In the fall of 2014 on the Beaufort Shelf, upwelling was the dominant mode of circulation, taking place more often than downwelling. This circulation structure means that DIC-rich water from the Pacific-origin layer is moved onto the shelf. Such upwelling can also bring water with high levels of DIC to the surface over the shelves. If the subsequent pCO_2 in the surface water is greater than the pCO_2 in the atmosphere, CO_2 may be transferred from the ocean to the atmosphere. An important chemical characteristic of this upwelled water is that it has low pH values. Lower pH means that the water is more acidic and therefore has a lower saturation state of aragonite and calcite, which are two calcium carbonate minerals that make up the hard structures of many marine organisms. A lower saturation state of these minerals means that organisms such as corals, molluscs, and crustaceans may have a harder time producing their hard shells or structures and may even dissolve.

With increased upwelling, the Mackenzie Shelf and its ecosystems are under more stress as high pCO_2 water alters pH conditions and the shelf becomes a possible source of CO_2 to the atmosphere. Changing ice conditions, river input, and atmospheric circulation are all altering how carbon is stored on the Beaufort Shelf. With such changes occurring in the Arctic, it is increasingly important to investigate and understand what is happening in these hard to reach locations. And although waking up at 3 A.M. to sample water isn't always a happy task, it is offset by calls to see the northern lights from the helicopter deck or watch polar bears swimming after your icebreaker. These moments make understanding the Arctic even more special.

THIS RESEARCH WAS FUNDED BY THE NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL (NSERC), NOVA SCOTIA GRADUATE SCHOLARSHIP (NSGS), AND ARCTICNET.

Jacoba Mol

Jacoba was born and grew up in Woodstock, Ontario, the dairy capital of Canada. However, she spent all of her summers in the seaside town of Gabarus, on Cape Breton Island. It's here, her love of the ocean and the need to understand it took shape. She took this love for the ocean and moved to Halifax in 2010, where she completed her Bachelor of Science in Chemistry and Oceanography at Dalhousie University. During her undergraduate degree, she had the opportunity to go on a cruise to the Arctic to measure dissolved inorganic carbon. With this experience, she gained an interest in water column chemistry, and a love for the Arctic Ocean and ship-based fieldwork. She continued at Dalhousie in the same lab group to complete a Master's degree, focusing on carbonate chemistry. She completed her MSc in June of 2017. If she's not on a boat in the middle of the ocean, you can find her playing inner tube water polo, sewing a quilt, or knitting a scarf.

Buffet or Drive-Thru?

Searching for potential right whale feeding grounds on the Scotian Shelf

Danielle Moore

Tiny food, big whale

Some might liken right whale feeding to a cow grazing on a field of grass; however, a more accurate comparison might be a cow grazing in the desert. These giant endangered carnivores feed on tiny crustacean prey the size of fleas, known as copepods. In the spring, copepods become quite abundant in Atlantic waters, but come July, they pause metabolic activity and sink to the seafloor. The ratio of an adult right whale's mass to that of a copepod is about 50 billion to one; similar to the size comparison of a human adult and a bacterium. Although tiny in size, these copepods are nutritionally packed with proteins and calorie-rich oils. In order to sustain day-to-day activity, an adult right whale needs to feed on roughly one billion copepods, or 2000 pounds, a day. To satisfy this high calorie requirement, right whales feed on ultra-dense aggregations of copepods rather than dispersed copepods so that their energy is not all expended on foraging.

Unlike other large predators, right whales do not manipulate their prey or environment in order to feed. Whereas lions run down their prey or dolphins herd a school of fish, right whales simply skim-feed by opening their mouths and

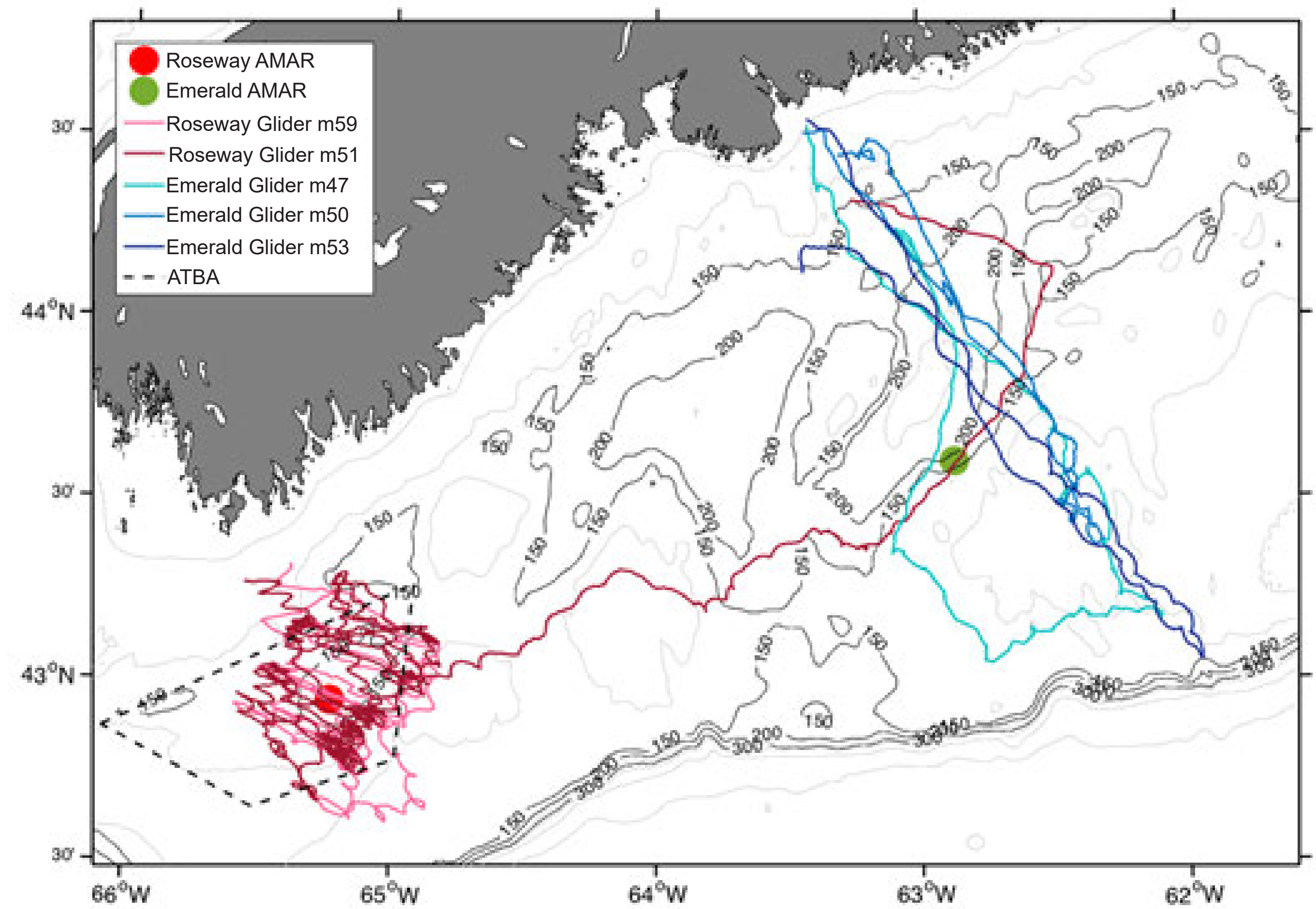


Figure 1. Map of the Scotian Shelf off the coast of Nova Scotia. The two fixed hydrophone platforms in Roseway and Emerald Basins are indicated by the red and green dots, respectively, and are approximately 210 kilometres apart. Red lines are glider tracks deployed over Roseway Basin and blue lines are those deployed over Emerald Basin. Isobaths (that is, lines of equal depth) in increments of 50 metres depth are also indicated.

moving towards their prey. In this sense, right whales rely entirely upon the environment to organize their prey into profitable, dense, aggregations for feeding. If scientists can locate and predict where and when these aggregations exist, it is likely that they may also be able to predict where right whales will be. Unfortunately, this work is a lot more complex than it sounds.

Complicating the issue further, right whale habitat occupation is known to vary from year to year, largely depending on food availability. For example, from 2010 to 2015, a well-known right whale habitat, Grand Manan Basin, was virtually abandoned by right whales. The abandonment coincided with an unusually low abundance of zooplankton in the region; while more than half the population was sighted in a new area that was experiencing an abnormally high abundance of copepods. This observation suggests that we may be able to discover new alternative right whale feeding habitats by following their prey. Dense aggregations can be indirectly inferred by searching for oceanographic processes that have been previously observed to concentrate copepods. For an ultra-dense aggregation to exist, at least three conditions must be met: First, a cavity in the seafloor, or a basin, must be present to allow for the collection of copepods. Second, copepods must be transported into the basin by currents, such as the influx of warm and salty water originating seaward of the continental shelf (the seabed where the sea is relatively shallow compared to the open ocean) within which copepods are abundant. And finally, certain biophysical processes, which are discussed below, are needed to densely aggregate copepods.

I investigated several biophysical processes that have been suggested to aggregate copepods in two well known right whale feeding habitats on the Scotian Shelf (Roseway and Grand Manan Basins). First, copepod avoidance of the turbulent waters near the seafloor, also known as the bottom mixed layer, may result in a vertically-compressed aggregation of copepods just above this layer. A habitat with a shallower bottom mixed layer depth would imply that a right whale would expend less energy by diving to shallower depths. Second, I searched for the presence and distribution of warm slope water containing

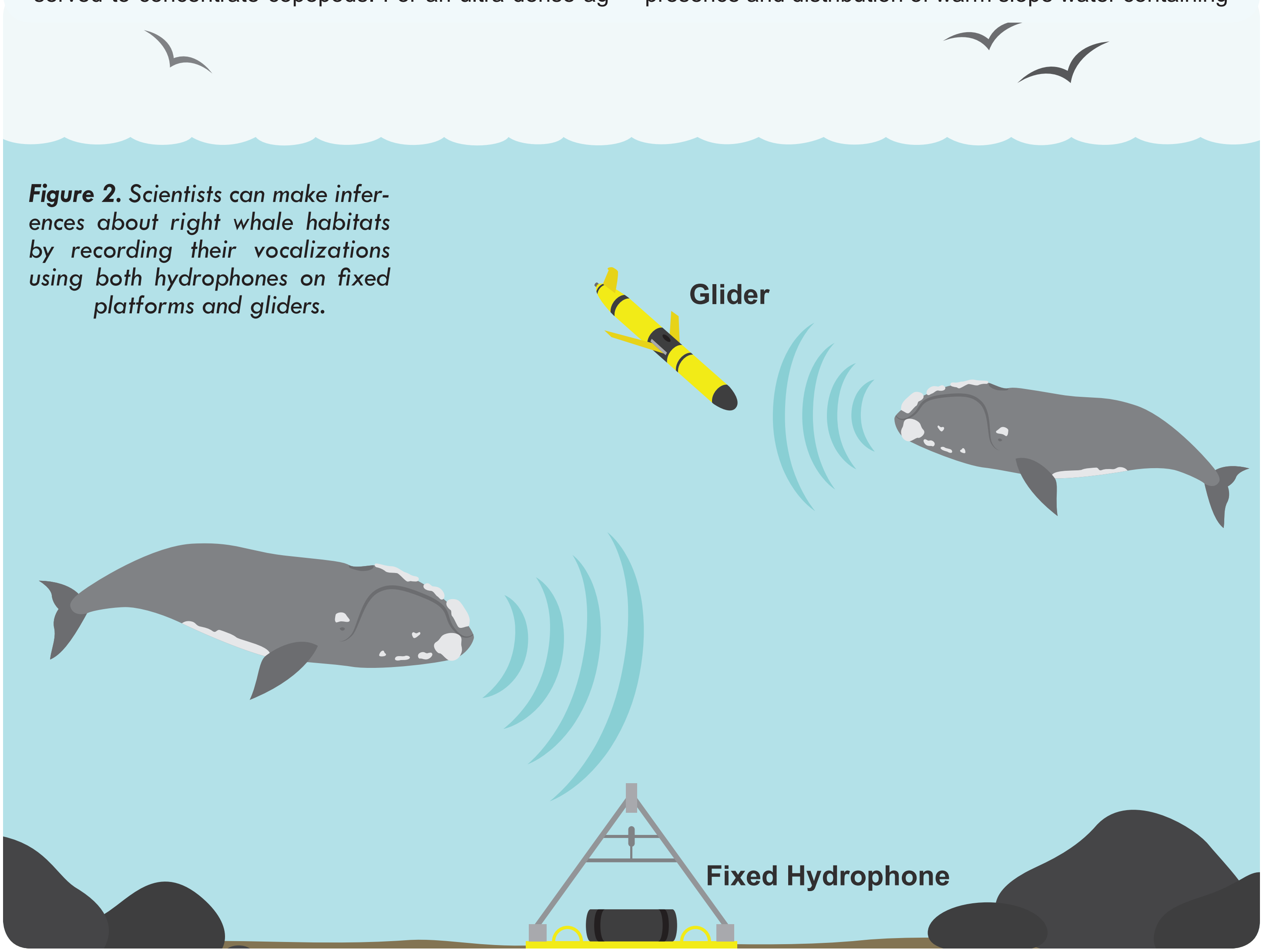


Figure 2. *Scientists can make inferences about right whale habitats by recording their vocalizations using both hydrophones on fixed platforms and gliders.*

copepods. A habitat with vertically-compressed slope water (that is, not distributed over a great depth) means that copepods have less vertical distance to roam and are subsequently aggregated. Finally, I searched for quick (about 0.2 metres per second; m/s) tidal currents, which may help in forcing and aggregating copepods against basin walls. By searching for these mechanisms along the Scotian Shelf, I may be able to infer whether a basin may act as effective foraging grounds for right whales.

Searching for the "buffet"...

The Scotian Shelf is a large subsurface geological formation (700 kilometres long and up to 230 kilometres wide), located southwest of Nova Scotia (Figure 1). Two basins on the Scotian Shelf were selected for this study: Roseway Basin, a well-known right whale feeding ground, and Emerald Basin, an underexplored potential right whale habitat. Roseway Basin is a shallow basin at roughly 180 metres depth; whereas Emerald Basin is deeper with a maximum depth of 291

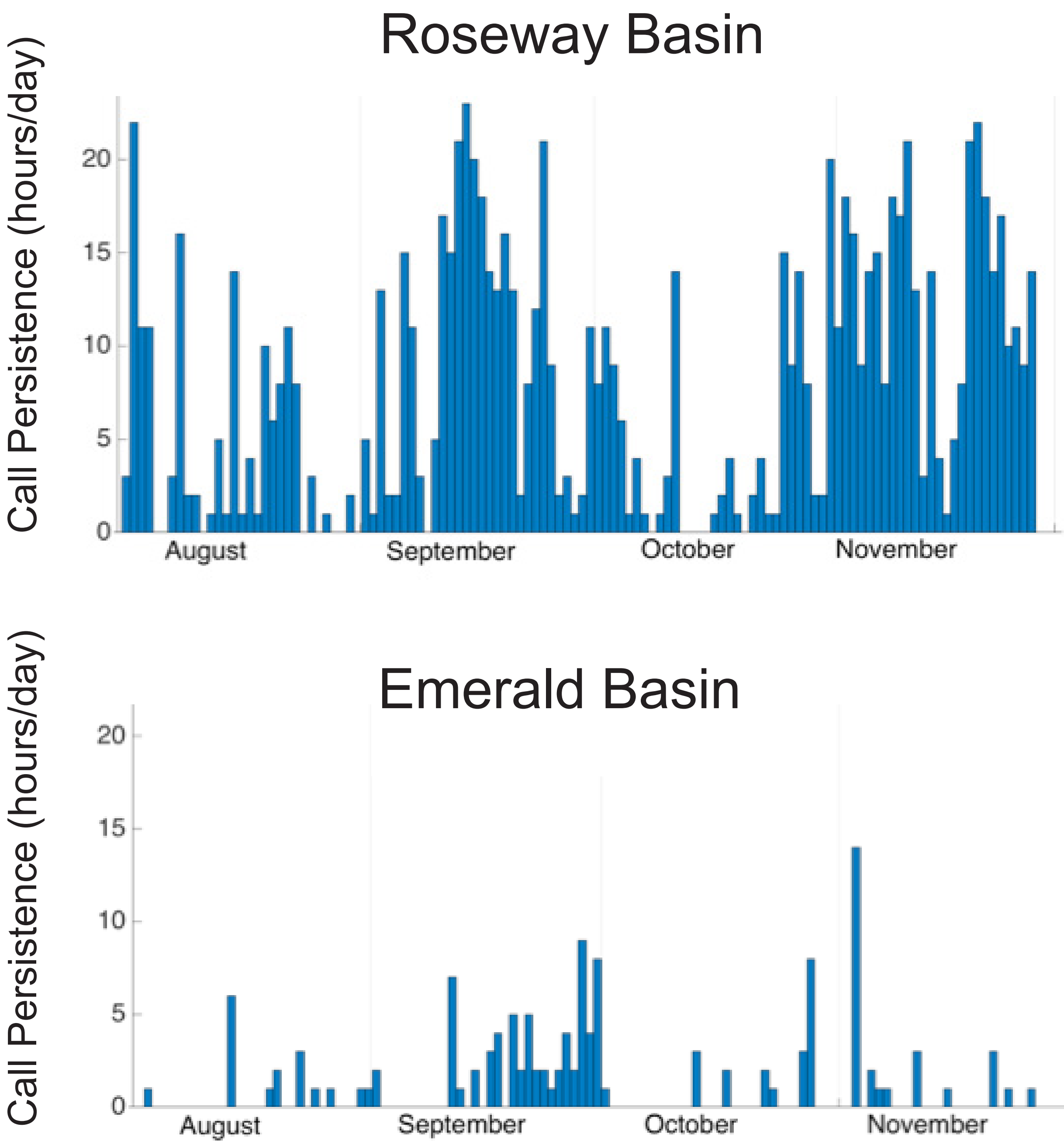


Figure 3. *Call persistence of the North Atlantic right whale from August 1, 2015 to November 26, 2015 in Roseway Basin and Emerald Basin recorded on fixed PAM platforms.*

metres. However, both of these basins contain continental slope water as well as copepods at depth.

My search for right whale feeding habitats involved a combination of two methods. First, I searched for the physical indicators of copepod aggregation in both basins using instruments attached to mobile Slocum Gliders that measure conductivity, temperature and depth (CTD) (Figures 1 and 2). Second, I inferred right whale presence by listening to acoustic recordings obtained using passive acoustic monitoring (PAM), a technique which relies on ambient ocean noise rather than actively sending out acoustic signals. Whereas visual boat surveys are high-effort, time consuming, and are often confined to good weather, PAM can record right whale vocalizations near-continuously in all types of weather. To explore temporal variation in right whale presence, a hydrophone was fixed to a platform (Figure 2) and deployed in each basin from August to November of 2015 (Figure 1). The acoustic recordings retrieved from these hydrophones were filtered using a right whale classifier. I then validated these sounds by visually inspecting the generated spectrograms for the upsweep pattern typical of right whale calls.

... Found a drive-thru

Using the CTD measurements, I found that the physical and biological characteristics in the two basins, although only 200 kilometres apart, are very different. For example, the bottom mixed layer in Emerald Basin is much deeper than in Roseway Basin, suggesting that right whales would have to expend more energy to dive deeper for their food. The water column in Emerald Basin also appeared to be less dynamic than Roseway Basin, with highly stratified waters and weaker tidal currents to aggregate copepods against basin boundaries. Finally, whereas the warm slope water associated with these copepods was found to be compressed against the basin seafloor in Roseway Basin, it extended up to 100 metres in the Emerald Basin water column. This finding implies that while copepods can be vertically dispersed over up to 100 metres in Emerald Basin, they have only a couple of metres to roam vertically in the preferred feeding habitat, Roseway Basin.

The results from the PAM recordings also indicate that Emerald Basin is likely not a preferred right whale feeding habitat in that there were far fewer right whale vocalizations recorded in Emerald than in Roseway Basin (Figures 3). This could be because right whales are residing in Roseway Basin for longer periods, or because more social activity is occurring, or perhaps a combination of both. Even though Emerald Basin appeared to not be a fundamental feeding habitat, there was still some right whale vocal activity present, suggesting that right whales may pass by this basin in search for more profitable feeding habitats farther north.

Oh whale: the search continues

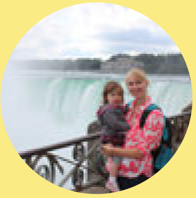
From this pilot study, I have determined that Emerald Basin was not a critical right whale habitat during 2015. While right whale vocalizations were recorded in Emerald Basin, there were considerably fewer calls relative to Roseway Basin. The stable environment in the deeper Emerald Basin most likely lacks the mechanisms required to aggregate dense copepod patches like in Roseway Basin. However, ephemeral food patches located in the depths of Emerald Basin may serve as a "snack" while right whales are passing by. These findings suggest that other deep basins along the Scotian Shelf, which may contain copepods, such as LaHave and Louisbourg Basins, may not have the necessary aggregating mechanisms to act as profitable right whale feeding habitats either. It is very possible that Roseway Basin is a unique feeding habitat, and perhaps the only "buffet" on the Scotian Shelf.

THIS RESEARCH WAS FUNDED BY NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL UNDERGRADUATE STUDENT RESEARCH AWARD (NSERC USRA).

Danielle Moore

After wrapping up her marine biology undergraduate degree, Danielle set out for a west coast adventure. Getting her hands dirty and living off-the-grid, Danielle is currently interning at a permaculture farm growing hops for craft breweries in British Columbia. She hopes to open up a sustainable urban aquaponics farm, but until then you can find her hiking up mountains, harvesting wild herbs and plants, and playing lots of music.

Where Are They Now?



***Carolyn Binder**, PhD - Defence Research & Development Canada*

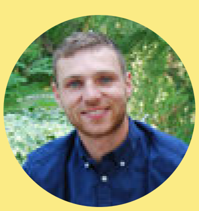
Since publishing her Current Tides article, Carolyn spent many long hours composing code, analyzing results, and writing her PhD thesis. All this work came to a happy conclusion when she successfully defended her thesis in July 2017. Since then Carolyn has been sure to take a few much-needed breaks to relax and come to the realization that a workday can end at 5:00. Carolyn continues her work at Defence Research and Development Canada (DRDC), where she has been a Defence Scientist since 2014. Currently, she's spending her time turning her thesis into a couple publications, and conducting ocean acoustics research. Specifically, she is leading the passive sonar signal processing work for DRDC's Arctic surveillance project. This includes developing algorithms to detect, identify, and determine the position of acoustic signals of interest. There is a strong focus on making this process fully automated since it will need to be performed on monitoring systems located in remote regions of the Arctic. During her recently rediscovered downtime, Carolyn enjoys spending time with her family, chasing after her active two-year old daughter, camping, and playing board games and video games with friends.

***Jessica Carrière-Garwood**, MSc - SCRIPPS Institution of Oceanography*

Shortly before defending her Master's at Dalhousie Oceanography, Jessica Carrière-Garwood started a PhD at the Scripps Institution of Oceanography under the supervision of Dalhousie-alumnus Peter Franks. Interested in physical-biological interactions, her current work focuses on plankton transport by nonlinear internal waves. To study these processes, Jessica deployed novel robotic plankton mimics in coastal waters off San Diego, California in June 2016. She is now interpreting the underwater tracks of the various 2-hour deployments with the help of some 2D models – stay tuned! When she is not on the water or in front of her computer, Jessica can usually be found climbing, a habit she picked up as part of the Seadogs climbing team.

***Diksha Bista**, MSc - University of Bristol*

Following her MSc in geological Oceanography at Dalhousie University, Diksha Bista moved to UK in 2015 to pursue a PhD degree in School of Geographical Sciences, University of Bristol. Her PhD is a part of a Marie-Curie Innovative Training Network project PRIDE, which aims to understand the current biodiversity crisis in the Black Sea and the Caspian Sea region. Specifically, her research focuses on reconstructing the connectivity history of the Black Sea and the Caspian Sea during the last 2 million years using strontium isotopes. She is currently in her third year of the project. In course of her PhD, she has participated in many fieldworks and cruises in the region, where she has collected sediment and water samples. Currently, she is dividing most of her time between lab-work analysing samples for strontium isotopes and writing her first thesis chapter. When not working, she enjoys reading fictions and likes to explore cafes and bars in Bristol.



***Mathieu Dever**, PhD - Woods Hole Oceanographic Institution*

Mathieu Dever defended his PhD thesis early 2017. He now holds a Postdoctoral Investigator position at Woods Hole Oceanographic Institution, working with Dr. Amala Mahadevan and Dr. David Nicholson as part of the NASA EXPORTS project. Mathieu's research focus is now on the impact of ocean circulation and flow instabilities on the export of particulate organic carbon from the mixed layer to the ocean interior. More specifically, how meso- and submeso-scale instabilities interact with the different particle sizes that are generated during a phytoplankton bloom. His objectives comprise investigating the size-differentiated sinking of particulate organic carbon, as well as developing optimized sampling strategies to properly measure the carbon export. To address these questions, Mathieu principally works with datasets previously collected in the north Pacific Ocean (gliders, moorings, sediment traps, etc.) and a process-oriented ocean model.

Elizabeth Kerrigan*, MSc - Dalhousie University*

After completing her Master's degree in April of 2015 Liz moved one building over, to the Steele Ocean Sciences Building at Dalhousie, to work as a research assistant in Dr. Wallace's CERC.OCEAN lab. Her job not only gives her the opportunity to continue the work on water isotopes that she began during her Master's degree, but allows her to learn a myriad of new laboratory techniques and operate new equipment. One of the main responsibilities of her job was the set-up, and now the use of, the laboratory's nutrient analyzer. In April and May of 2017 Liz was able to participate in a research cruise across the North Atlantic, from St. John's to Galway, Ireland onboard the R/V Celtic Explorer. Using her sea-going laboratory container, she packed up her nutrient analyzer and brought it with her across the (sometimes very rough) Atlantic Ocean. While most of her days are spent in an air-conditioned lab, being able to go to sea, or even to Bedford Basin, makes doing ocean research exciting, and she will hopefully be able to go on more adventures in the future.

Clark Richards*, PhD - Bedford Institute of Oceanography (DFO)*

After finishing his PhD in 2012, Clark started a position as a postdoctoral investigator at the Woods Hole Oceanographic Institution in Cape Cod Massachusetts. Working with Dr. Fiamma Straneo, his focus shifted from studying mixing in the St. Lawrence Estuary to higher latitudes. For his primary project, he studied the roles of air-sea interaction and mesoscale eddies on watermass transformation in the Nordic Seas. He also got involved in a project studying ocean-glacier interactions in Greenland, and spent several weeks in 2013 collecting data in a Greenland fjord. Following this, he took a position with a private company (RBR, Ottawa) that designs and manufactures ocean sensors and instrumentation. At RBR, Clark worked to help the company to better connect with the scientific community and to evaluate sensor performance for uses such as the Argo program. In September 2016, he started a position as a Research Scientist with Fisheries and Oceans Canada at the Bedford Institute of Oceanography. In this new position, he is working as a scientist with the coastal glider program, and is the principal investigator of the Barrow Strait Monitoring Program.

Justine McMillan*, PhD - Rockland Scientific International*

Justine defended her thesis in June 2017 and promptly moved to Victoria, British Columbia to take up the role of "Staff Scientist" with Rockland Scientific International. The small – but growing – ocean instrumentation company specializes in the measurement of turbulent flows and ocean mixing. Her position with Rockland is a direct result of a field experiment that happened two years after she started her PhD. They collected a dataset that "…would make for a great thesis" (quote from Rolf Lueck, her current boss). So there she was, two years into her degree, and essentially starting her research from scratch. But, Rolf was right – it was an extensive dataset that yielded interesting results, and a great job! As "Staff Scientist", Justine spends her days learning about turbulence in the ocean, which in turn, allows her to enable science. She provides technical and scientific advice to their customers and, in many ways, she acts as a liaison between Rockland's engineers and the broader scientific community. She also gives presentations at conferences and provides training courses to teach scientists about turbulence. So, good communication is clearly a critical aspect of her job and her involvement in Current Tides, as both an author and Editor-in-Chief, was invaluable. Six years ago – when she started my PhD – Justine would not have expected to be communicating science on a daily basis. Believe it or not, she was painfully shy for the first 25 years of her life. But, by having an open mind and always keeping the door open to new opportunities, she has found a career path that is unique and exciting!

William Burt*, PhD - University of British Columbia*

Will finished his PhD at Dalhousie in May 2015, and got married 4 months later! In 2016, he moved back to his hometown of Vancouver, BC to begin a NSERC Postdoctoral Fellowship at the University of British Columbia. This cross-country move also included a shift from chemical oceanography into biological oceanography, which has enabled him to expand his knowledge base and learn a new set of oceanographic skills and tools. His research now focuses on measuring primary productivity, the growth of tiny marine algae (also known as phytoplankton) that make up the base of the marine food chain. Just like his PhD research, Will continues to go out on research vessels to collect his data at sea, but rather than measuring carbon and radium in the North Atlantic, he now uses measurements of light to estimate phytoplankton biomass and growth rates in the North Pacific. In 2017, Will embarked on his greatest adventure yet, becoming a dad! His son Callum is now 3 months old and both Will and his wife Jen could not be happier. Will's life outside of research is still much the same; he still plays various sports, hikes, and climbs. The only difference is, he now enjoys these activities with his beautiful family!

Thank You!

Close your eyes, take a deep breath...It's done, and WE did it!!!

As Editor-in-Chief of Volume 3 of *Current Tides* I would like to thank each single person that took time to put this magazine together, both authors and editors. Although I was an editor in the Volume 2 myself, and already went through all drafts and edits before, I would have never anticipated the amount of collective effort, time and energy that *Current Tides* requires. In the same way I am sure that none of the authors or editors realized what they would be going through when they first volunteered for writing or editing the articles. They probably didn't even think it was possible to receive so many emails from me with a big URGENT on the subject line. Nevertheless you were all very responsive and helpful every single time so THANK YOU. I am proud of what we achieved as a team, the articles and the research they describe are reflective of the amazing and diverse research going on in our Department, and I think everybody should be proud of this. I am particularly thankful for being able to add an undergraduate student's article (Danielle Moore) to this edition of the magazine because it reflects that our Department is able to offer fantastic opportunities not only to graduate students.
I owe a huge thank to Justine McMillan (Editor-in-Chief of Volume 2), that was always there to help me and answer my questions while writing her thesis and even after moving to Victoria to pursue her career. Thank you for believing that I could take this role before even I could think so!
Furthermore I would like to thank the Department of Oceanography for the continuous support to this student initiative, the Dalhousie Oceanography Student Association (DOSA) for the collective excitement to read and promote the magazine in different venues and our graphic designers James Gaudet and Tracey Hachey for the hard work and patience.
Finally I would like to personally thank all our sponsors for making all this happen and for believing in this project.

Lorenza Raimondi
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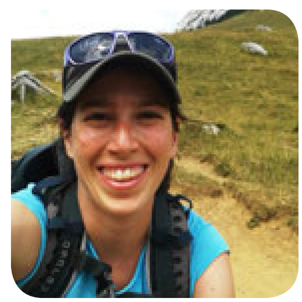

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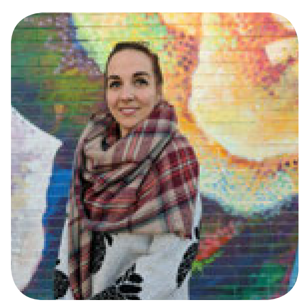

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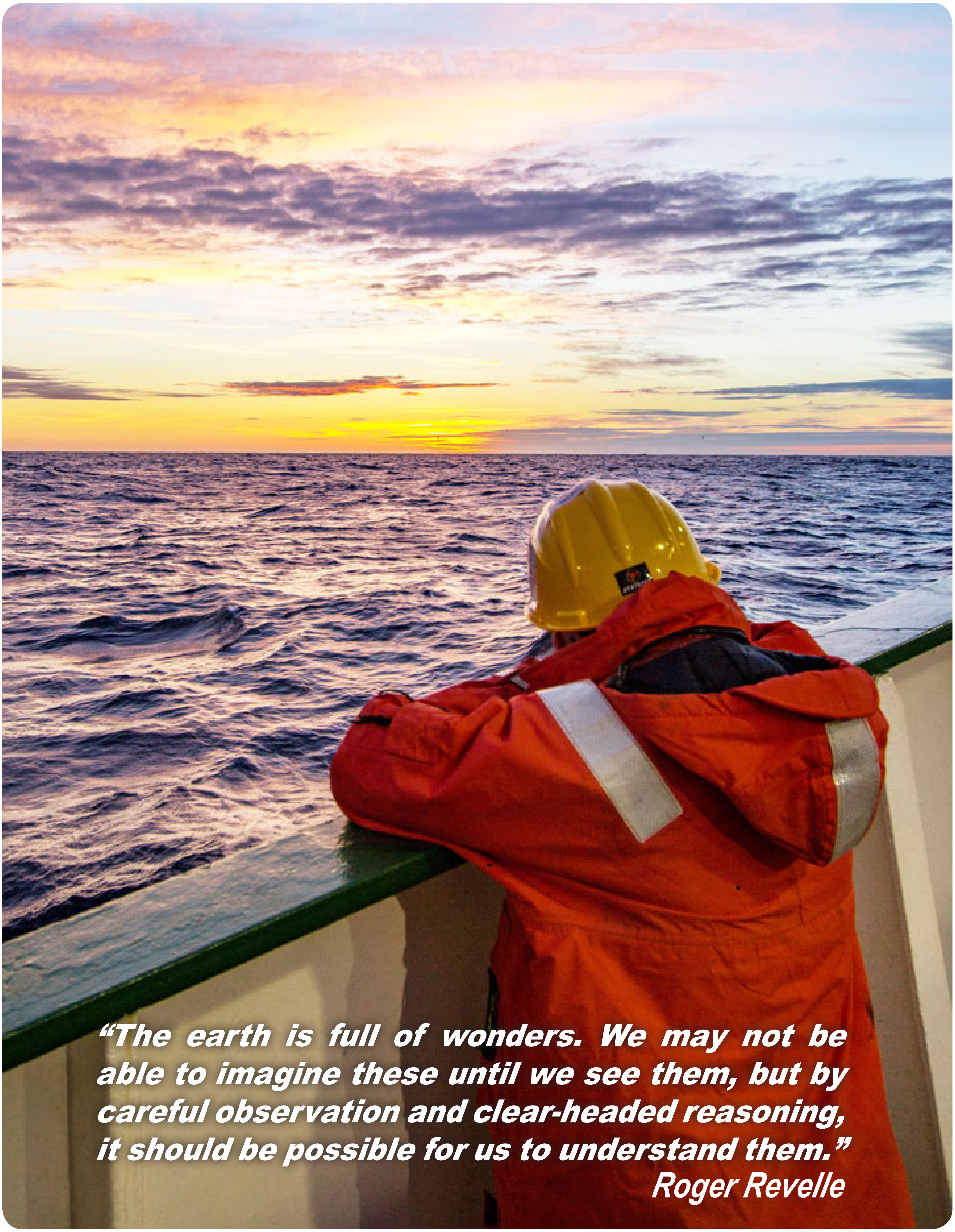
"The earth is full of wonders. We may not be able to imagine these until we see them, but by careful observation and clear-headed reasoning, it should be possible for us to understand them."
Roger Revelle

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