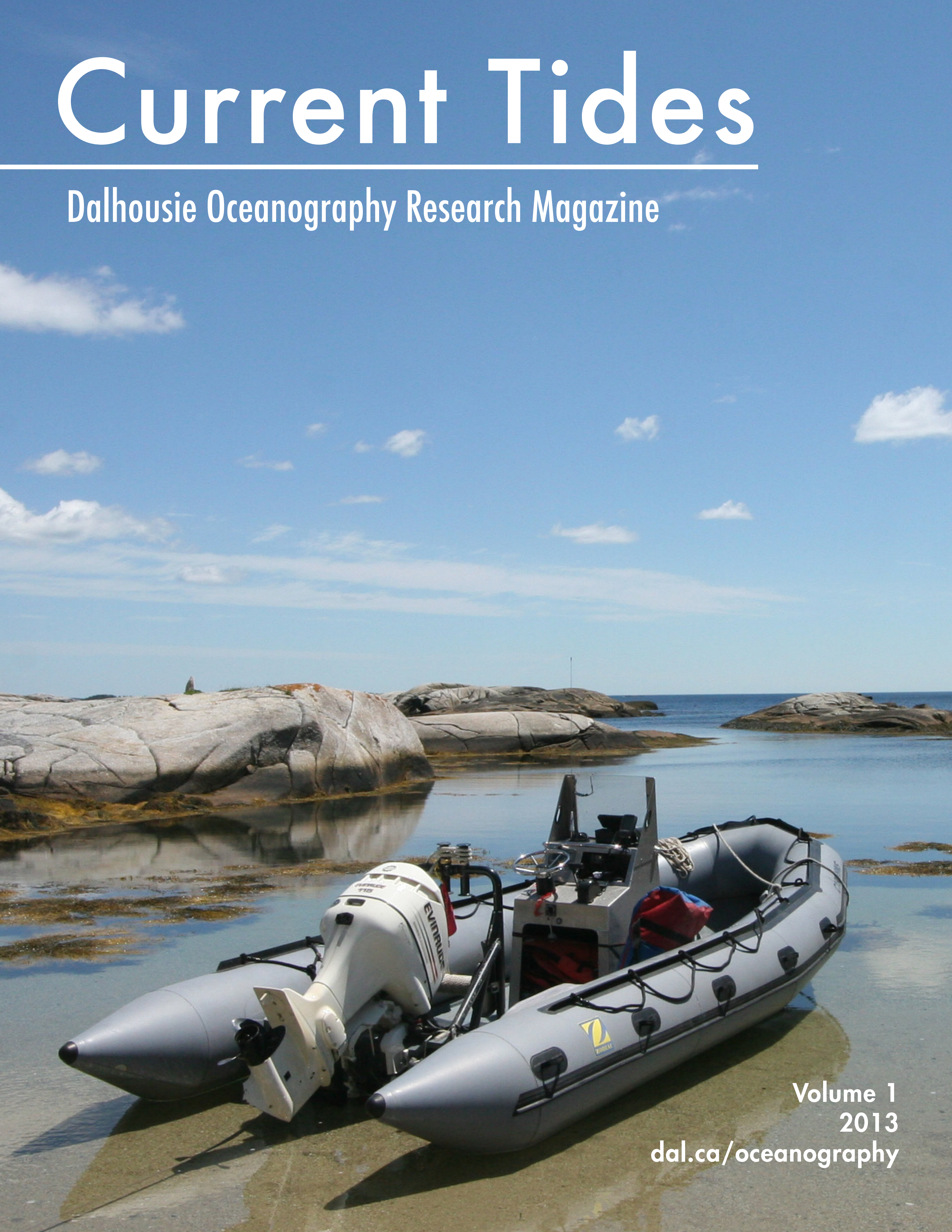
Current Tides

Dalhousie Oceanography Research Magazine



Volume 1
2013
dal.ca/oceanography

Current Tides

All article photographs/figures were provided by authors unless credited otherwise
Cover: Photo courtesy of Matthew Hatcher
Back: Photo courtesy of Clark Richards

Editor-in-Chief: Franziska Broell
Editors: Mathieu Dever, Janelle Hrycik
Supporting Editors: Jean-Pierre Auclair, CarolAnne Black, Liz Kerrigan
Financial Manager: Franziska Broell

Print Design: James Gaudet
Graphic Design: www.tandemhalifax.com
David Cullen, Quinline Graphics (p. 17, p. 24)

To send letters to the Editor and (or) receive the print publication, email: currenttideseditor@phys.ocean.dal.ca
or visit www.currenttides.ocean.dal.ca

2013, Department of Oceanography
Dalhousie University
1355 Oxford Street
Halifax, NS, CANADA, B3H 4R2

A Letter From the Chair

It is my very great pleasure to introduce the inaugural issue of Current Tides. The expositions of graduate student research in the following articles convey very nicely the breadth and depth of research activities in the Department of Oceanography at Dalhousie University.

Dalhousie University is Canada's ocean university. The University sits on the peninsula in Halifax, surrounded by the sea both physically and in terms of the marine industries and activities that shape the existence of Nova Scotia - as much now as they have for the last centuries. The Department of Oceanography is one of the world's leaders in ocean science, technology and education, and the work discussed herein reflects this.

The research spans a broad range of activities from laboratory research (see Nick's poetic discussion of the Dance of Bobbing Henry) to muddy tidal flats (Jessica) to coastal ocean geochemistry (Will) to the planetary albedo of the entire Southern Ocean (Mike). Characteristic of most, if not all, of the research is an interdisciplinary approach to the field, one of the fundamental bases of modern oceanography. Fish, for example, exist within a fluid medium and their behaviour can only be appreciated through a keen knowledge of the mean currents, tides and small-scale mixing in the waters where they spend their existence, as shown for both large fish (Franziska) and small (Janelle). New attempts to answer oceanographic questions often involve development of new technology and instrumentation as seen throughout the articles; they also include close coupling with novel analytical and theoretical approaches which are evident in Justine's work on small-scale tidal flows and Clark's larger-scale approaches to estuarine mixing.

The authors reflect the diversity of our graduate student body - 50% are women and 50% are from outside Canada. This makes for a vibrant and interesting student body as we continue to contribute to the global Dalhousie Oceanography diaspora!

Finally, I would like to extend my sincere thanks to the Editor-in-Chief, Franziska Broell, the editorial staff, and the print and graphic designers. This is a wonderful initiative that will be an inspiration for both faculty and future generations of students. Bravo Zulu!

Marlon Lewis, Chair of the Department of Oceanography

Contents

Fish and Chips

A new technology to measure fish behaviour, activity and growth

One of the accelerometer tags that we developed in collaboration with Andre Bezanson. In the background is the tank used for mesocosm accelerometer studies with cod and pollock. Photo credit: Danny Abriel.

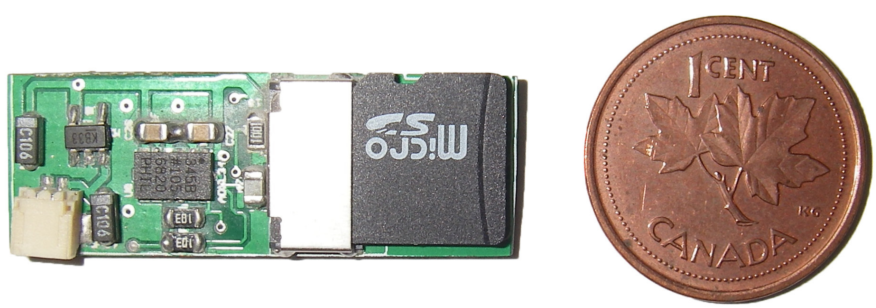
Franziska Broell

Prying into the private lives of animals

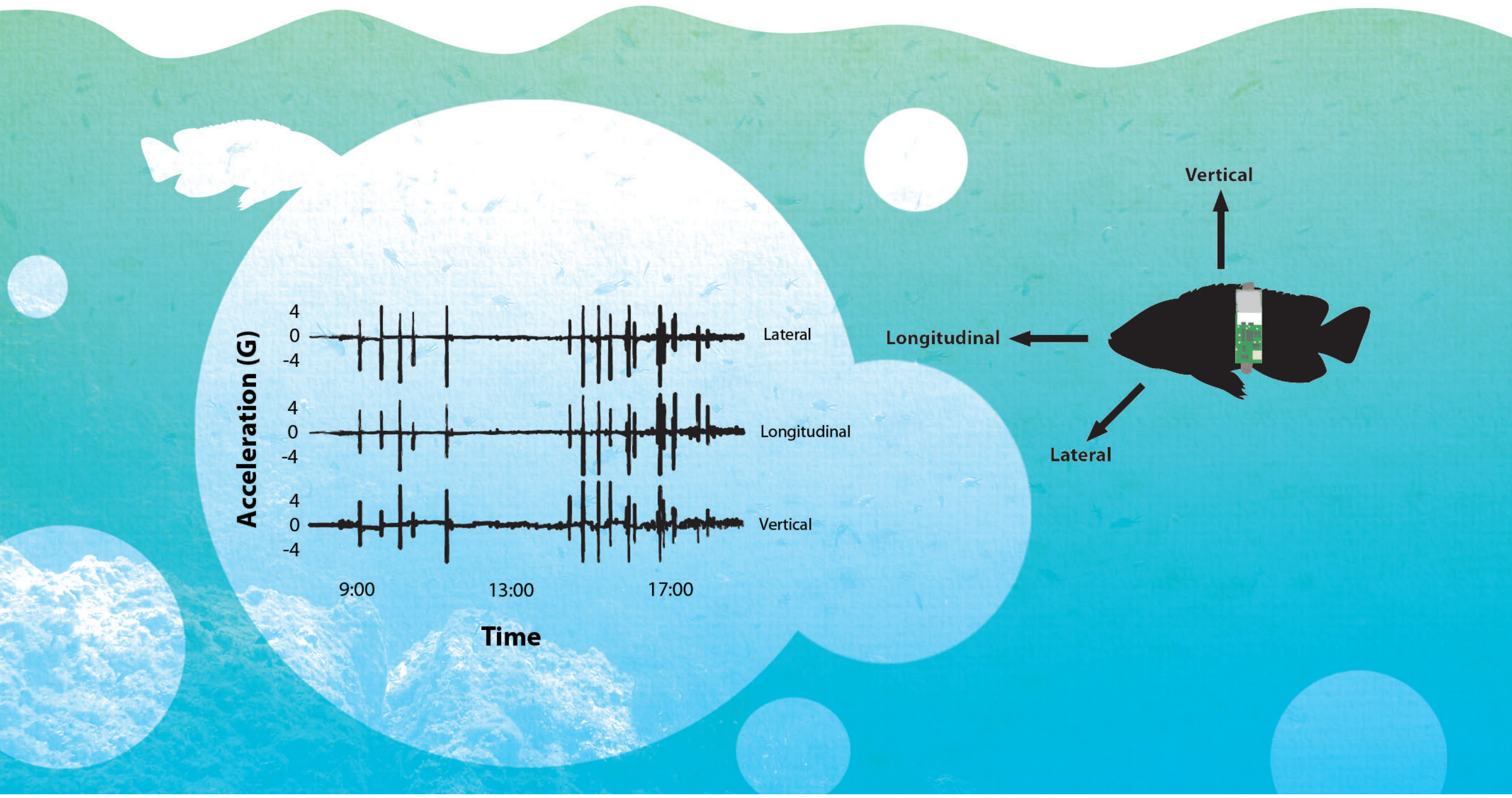
When studying animals that live in the ocean, the very environment presents a significant barrier. The sea is a large and often hostile environment, where visual observations are sparse and haphazard, making it difficult to find out where animals are or what they are doing. New advances in tagging technology have started to fill in some blanks. We are now able to collect information on the animals' surrounding environment - things like temperature, salinity and the vertical (depth) and horizontal (GPS location) distribution of the animals on large time and space scales. The tags can send these kinds of information to receivers anchored on the ocean floor or to orbiting satellites, allowing us to easily access the data. Unfortunately, most of the available tags are too large to attach to smaller animals, such as a commercially valuable fish species, and/or provide only rough estimates on the distribution of individual animals and very little information on their behaviour. Fortunately, a new technology is on the horizon: movement-sensing accelerometer tags. Anyone with a smartphone is familiar with what accelerometer chips do, even if they have never heard of them before. By sensing the movement and tilt of the device, the phone's chip can tell which way the screen is being held, allowing for automatic adjustments. These tiny chips are all around us; they are used in monitoring nuclear reactors, in diagnosing the onset of diseases such as arthritis or Parkinson's, and they can even save lives by detecting a car crash and triggering airbag deployment in fractions of a second. This same technology that can make our lives safer, healthier, easier and more fun can also provide insights into the daily lives of animals in the ocean.

Plug and play

Accelerometers measure changes in gravitational pull or movement, which occur when an animal moves, providing us with indirect measures of what the animal is up to. For example, an accelerometer can detect the movement of a fish's tail, which tells us how fast it's



The micro-accelerometer tag, capable of recording tri-axial acceleration at up to 550 times per second. With this technology we are able to capture behaviour that occurs over very short time scales, such as a fish feeding on prey or escaping from a predator. Such behaviour-associated movements can occur within the blink of an eye.



An example of the type of data that is recorded with accelerometer tags in laboratory experiments. Data are recorded at 100 Hz, and we can observe several behaviours that include swimming, feeding and escaping from a predator.

swimming and how much energy it's expending. It can also be used to measure the fish's growth rate, which is essential in estimating stock size and important for fisheries management. For example, when a little fish swims at the same speed as a big fish, the little fish has to beat its tail much faster. It's very similar to a child walking next to his parents; the child has to move his legs much faster to keep up with his parents' stride. Based on this idea, we can relate the size of a fish to how often it beats its tail, which, over time, allows us to get estimates of the growth of the animal in its natural environment - something never achieved before.

The steep learning curve

When I arrived at Dalhousie University to pursue my PhD, my advisor Dr. Christopher Taggart had a challenge waiting. He presented me with a box full of circuit boards and wires and said, "Here. That's your project". It turns out that while, in theory, the technology for accelerometer tags exists, the commercially available tags had some drawbacks. They are large, expensive and only record at low frequencies (up to 32 Hz, which is 32 times per second) – too low to detect very fast movements that occur in fish when fish swim in schools, escape from predators or catch their own dinner. So it was up to me to develop a unit that could do exactly that.

Without much of a background in electrical engineering, it took me quite a while to wrap my head around the problem. While I was slowly starting to build my own simple circuit boards, I had a stroke of luck. Through mutual friends, I met engineering PhD student Andre Bezanson, who was fascinated by my project and was eager to help me. Together, we have developed a unit that is ready for use in field and laboratory research. It is very small, about half the size of an SD memory card, cheap and capable of recording and saving acceleration data at very high frequencies (up to 550 Hz). By temporarily attaching these tags to fish, we can record their movements and download the saved data when the tags are retrieved.

From the lab to the field

To test the technology, we first obtained movement data in laboratory experiments using Atlantic cod and Atlantic pollock in a large-scale tank at the Dalhousie Aquatron facility. This allowed us to study the fish in

A school of Atlantic cod equipped with micro-accelerometer tags swimming in an experimental mesocosm in the Aquatron Facilities at Dalhousie University. From these data we can get information on behaviour and activity in a near-natural environment.

their near-natural habitat while incorporating visual observations. Such observations are crucial in relating the accelerometer signals to animal behaviour.

After spending a summer in the lab, I was eager to see if the tags measured up in the real world. To observe fish in their natural habitat, we had to overcome several challenges. If you tag a fish in the ocean, chances are, you won't find it again. Unfortunately, to get our data back, we need to find our fish and physically retrieve our tags. For that purpose, we paired up with a company that produces Pop-up satellite archival tags (PSATs). These tags record information on depth, temperature and light. After some pre-set time, the units pop off and they rise to the surface where they transfer data to an orbiting satellite that can be downloaded from anywhere in the world. With the help of the satellite, we can also pin-point the location of the PSATs and recover them, making them the perfect instrument to carry our accelerometers.
We employed this system with shortnose sturgeon in the Kennebecasis River in New Brunswick, Canada. Using fish in a river system increased our chances of retrieving the tags. And it worked! Not only did all our deployed tags pop off the fish, but we were able to retrieve them afterwards.

An ocean of data

From these lab and field experiments, we managed to obtain thousands of hours of movement data on several species of fish. In the field, the accelerometer tags record acceleration in all three dimensions (forward/backward, left/right, up/down) 50 times a second, plus water temperature, depth and light measurements; the data set is immense. While it is crucial to record at high frequencies to capture data on very quick and fast movements, it means that we have to figure out an automated way to extract the most valuable information. On top of the sheer size of the datasets, we need to be able to relate acceleration signals to the behaviour of the animal. Simple movements like the tail beat are easily extracted from the acceleration signal and can be used to estimate growth rate and energy expenditure. However, other types of move-

Releasing a shortnose sturgeon in the Kennebecasis River in New Brunswick. The sturgeon is equipped with a micro-accelerometer tag and a PSAT tag that serves as a carrier unit. After 48 hours, the release pops off the tag and it floats to the surface where we can locate it through the ARGOS satellite system. This allows us to physically retrieve the tag and the information that is stored on it.

ment that occur when the animal is feeding, or darting away from a hungry predator, are not well described and difficult to sort out. First, we have to relate the accelerometer signal to some visually observed movements and behaviour and then design a computer algorithm that automatically does the same.

Along the way, we are also getting a more detailed picture of the lives of the tagged animals. The acceleration, temperature, pressure and light data obtained from the shortnose sturgeon swimming in the Kennebecasis River provides information on what the fish were up to after we let them go with their tags attached. For example, we have already discovered for some of these fish, their activity in the river seems to be related to the tidal cycle – yes, the ocean tide propagates up the river – indicating that they may be exploiting the tidal current to save energy during swimming. In others, the amount of sunlight reaching the bottom appears to have a negative effect on their activity – fish tend to expend less energy during the day than at night.

Using this approach on one species, we have successfully developed an automated system that tells us whether the fish was simply swimming along or making sudden turns or feeding or escaping from a hungry predator. All of this is achieved with the algorithm; it identifies the behaviours simply by using the movement signal captured by the accelerometer tag. This is somewhat of a breakthrough in the monitoring of fish and could be easily transferred to other marine species such as seals or penguins, making this a powerful tool in the research of marine animals in the wild.

Taking it to new depths

Our next step is to code the step-by-step automated procedures into a microprocessor integrated on the accelerometer tag. This means in the future we won't end up with hundred of hours of acceleration data, but with detailed information about the activity and behaviour of the animal over time, whether it be feeding, sleeping, spawning or simply migrating. Our goal is to combine this with other technologies, such as the PSAT, which could allow us to determine the spawning or feeding grounds of a marine animal - invaluable information for the management and conservation of endangered and economically valuable species.

THIS WORK WAS FUNDED BY THE OCEAN TRACKING NETWORK CANADA – NSERC STRATEGIC NETWORK GRANT.

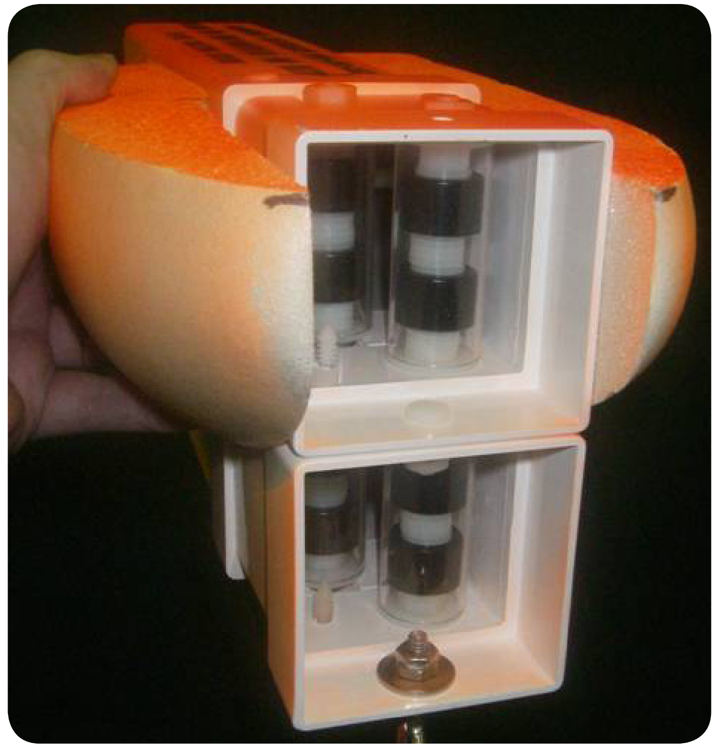
Franziska Broell

Originally from Germany, Franziska Broell first came to Dalhousie University as an undergraduate exchange student in 2007 from Wellington, New Zealand, where she was majoring in marine biology. When she completed the Fisheries Oceanography course with Dr. Christopher Taggart, she quickly discovered that to get ahead in the game, she needed to improve her quantitative skills. Returning to New Zealand, she added a major in Statistics and completed her Honours degree in the Statistics Department. When Dr. Taggart proposed the accelerometry PhD project, she didn't hesitate without knowing what she was really going to get into. Most recently her efforts with Andre Bezanson led them to found *Maritime bioLoggers*, a company specializing on the development of low-cost micro-accelerometer tags. When not tagging fish, she enjoys cooking, crafting, hiking and visiting her family in Germany.
Photo credit: Danny Abriel.

MAP-ing Where Things Go

New technology to measure dispersal in the coastal ocean

Janelle Hrycik



Leading-end of a magnetic collector, designed to capture near-surface and subsurface MAPs.

As a baby lobster drifting at the will of the ocean, where do you go? You might travel back and forth with the tide or get sent further out to sea by a current. Your survival depends on where you end up. When you begin to grow and settle to the sea floor, is the environment there to your liking? Are there other lobsters around that you can court? When you leave your mom, much of what determines where you end up is out of your control. Nearly all of the movement of a lobster occurs when it's a baby. This is when it's so small that it can be carried great distances by a current or two. It's important for scientists to know where these baby lobsters end up after their travels, as the lobster is a commercially valuable species - everyone wants to find, catch, and eat them. Knowing something about where the lobsters settle to begin their adult lives can help us manage the fishery. So, how do scientists know where things like baby lobsters go in the coastal ocean? Well, it turns out that the ocean is pretty good at hiding the answer.

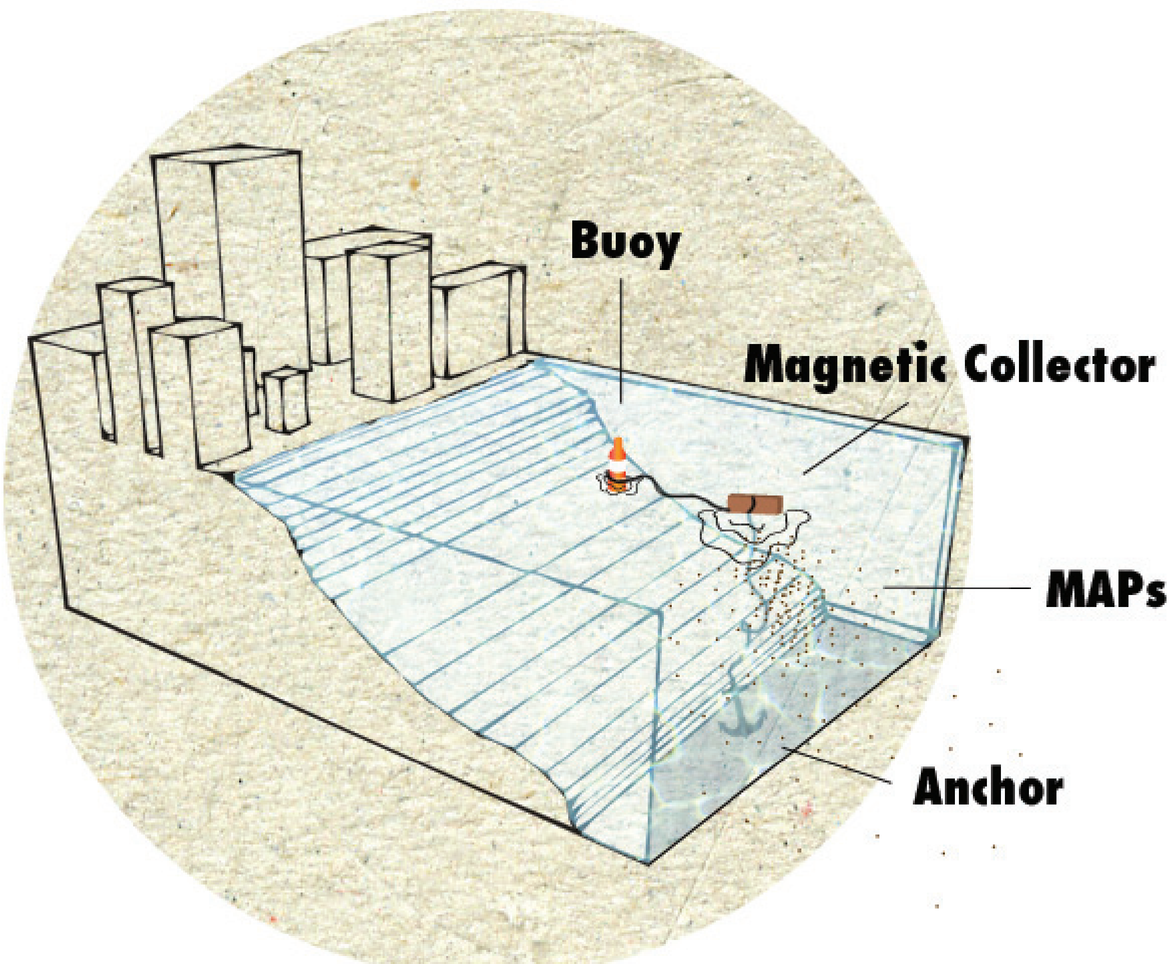
To answer this question, we study what is called marine dispersal. In our story, dispersal refers to the spread of baby lobsters away from their mom through both passive (ocean currents) and active (swimming) means; however, in the ocean, the passive component is especially important. Dispersal affects the distribution of individuals, and ultimately reproduction, gene flow and thus the spatial scale of population connectivity through the exchange of individuals among geographically separated subpopulations of the species. Scientists often define dispersal in terms of the dispersal kernel, which is a function that describes the probability that something like a baby lobster will end up at a given location, measured as a distance from where it started.

Marine dispersal questions like where things go, how they're mixed, and what the time and space scales are have typically been answered using conventional tracing technologies - drifters, dye and numerical models. Unfortunately, there are well-known limitations with all of these methods. Releasing many drifters can become costly; you have to chase them (to find them) when the experiment is over, and most importantly, they are not at a particle (i.e. baby lobster) scale. This means that since they sit well above the ocean's surface after deployment, they are much more affected by wind than a baby lobster would be. In addition to becoming costly in terms of ship and survey time, dye becomes too dilute to measure after a few days, and you can't be in all places at all times to measure it. Numerical models require computing power and time, have unknown parameters and are rarely compared with measurements in enough detail to ensure they are

Sample of MAPs floating in salt water.

doing a good job reflecting reality. Not to say that some aren't useful, but all models are imperfect in ways that are impossible to determine. So, to answer our question, wouldn't it be nice to have inexpensive particle-sized (i.e. baby lobster - sized) drifters that overcome many of these issues?

In my research, with advisors Drs. Christopher Taggart and Barry Ruddick at Dalhousie University and collaborator Dr. Joël Chassé at Fisheries and Oceans Canada, I study marine dispersal using a new technology - magnetically attractive particles (MAPs). MAPs are particle-sized drifters that are made of hollow glass for buoyancy, magnetite to make them magnetically attractive and food safe epoxy to hold it all together. They're each approximately the size of a grain of sand, and they're designed to mimic things like baby lobsters that passively float in the surface layer of the ocean. After releasing MAPs from a known starting location, we can collect them days or even weeks later in moored magnetic collectors. The tiny magnetically attractive particles disperse throughout the surface layer of the ocean.



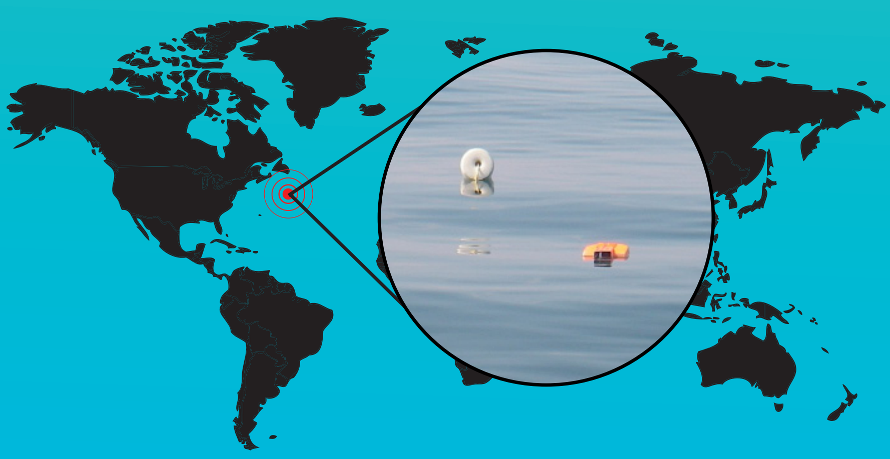
When water containing MAPs flows through one of the magnetic collectors, the MAPs are captured by the magnets. The magnetic collectors act like a net, collecting everything that comes in and nothing more. When we retrieve the magnetic collectors, we can count the number of MAPs caught by each collector.

These data give us a probability distribution of where MAPs go by purely passive means after being released from their starting location. This means that if baby lobsters left their mom at the location where we released MAPs, we would know where they end up by simply drifting in the ocean.

MAPs provide what we call the biological *null model* – the passive (physical) component of marine dispersal. Only when this null model is achieved can we expect to accurately incorporate biological processes such as birth, behaviour and death into the numerical models we typically use to answer marine dispersal questions.

A single MAP experiment provides an observational estimate of dispersal, a quantity that has been historically difficult to directly measure in the ocean. This is important because in many cases, numerical models are used as a central tool in marine conservation and management decisions, and observational estimates of dispersal are necessary to assess these models. MAP experiments can test the model's capabilities, which has the potential to result in more informed conservation and management decisions for commercially valuable, endangered and invasive species. From MAP analyses, we have determined that semi-enclosed water masses need to be treated differently than open-ocean water masses when calculating dispersal kernels. When comparing the MAP results with similar numerical model results, we have found that the value of the modelled small-scale diffusion (i.e. mixing on scales smaller than the model grid) impacts the strength of agreement. Additionally, we have found that models used for dispersal and connectivity may be too spatially conservative in their estimates. This means that if a model is being used to define the boundaries of a new Marine Protected Area, then the boundaries wouldn't extend far enough to adequately protect the species that use dispersal as a means of distributing individuals. Linking the empirical (MAPs) with the theoretical (models) is a critical step for advancing the study of dispersal.

In addition to answering questions about things like baby lobsters, the MAP and magnetic-collector system can address a plethora of other problems. MAPs can be used to answer questions relating to invasive species dispersion (e.g., What areas will non-natives become problematic?), transport and dispersal in aquaculture settings (e.g., Is there a risk of disease spreading between farms or to wild populations?), and



An anchored magnetic collector floating in the surface layer of the ocean with the top of the upper tube peaking above the surface. Photo Credit: Matthew Hatcher.

the tracing of contaminants (e.g., Where will oil spread on the surface of the ocean if there is an oil spill?). MAPs can also be modified to answer questions in areas other than the surface of the ocean, and can be used to study sediment transport on the ocean floor or erosion of soil and nutrients into rivers. The MAP and magnetic collector system helps us answer the difficult questions about where things go in the ocean, and it's likely that there are other uses for this system that we haven't even thought about yet!

THIS RESEARCH IS SUPPORTED BY THE FISHERIES AND OCEANS CANADA NORTHUMBERLAND STRAIT ECOSYSTEM RESEARCH INITIATIVE (NSERI) AND THE NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL (NSERC) CANADIAN HEALTHY OCEANS NETWORK (CHONE). TECHNICAL DEVELOPMENT FUNDING WAS SUPPORTED BY THE WORLD BANK/GEF, THE NATIONAL SCIENCE FOUNDATION, THE NSERC IDEAS TO INNOVATION PROGRAMME, AND THE INNOVACORP I-3 TECHNOLOGY START-UP COMPETITION.

Janelle Hrycik

Janelle Hrycik grew up in Colden, New York, and first became excited about the ocean while watching *Free Willy* over and over as a child. She later became hooked on science in high school while competing in regional and state Science Olympiad and Envirothon competitions. After deciding to pursue her interest in biology in combination with her love of whales as a career choice, she earned a Bachelor's degree in marine vertebrate biology from Long Island University – Southampton College in 2008. Needing more of a challenge, she moved to Nova Scotia to pursue a PhD in biological oceanography, working with advisors Drs. Christopher Taggart and Barry Ruddick. While no longer working with whales, she is excited to be involved with such a cutting-edge project. When not counting particles or struggling with MATLAB, she enjoys travelling to new places and spending time with her husband, Chris, and their two cats, Phoebe and Cassie. Photo Credit: Danny Abriel.

Are Mud Particles Simply Very Small Sand Grains?

How and why scientists measure sediment grain size

Jessica Carrière-Garwood

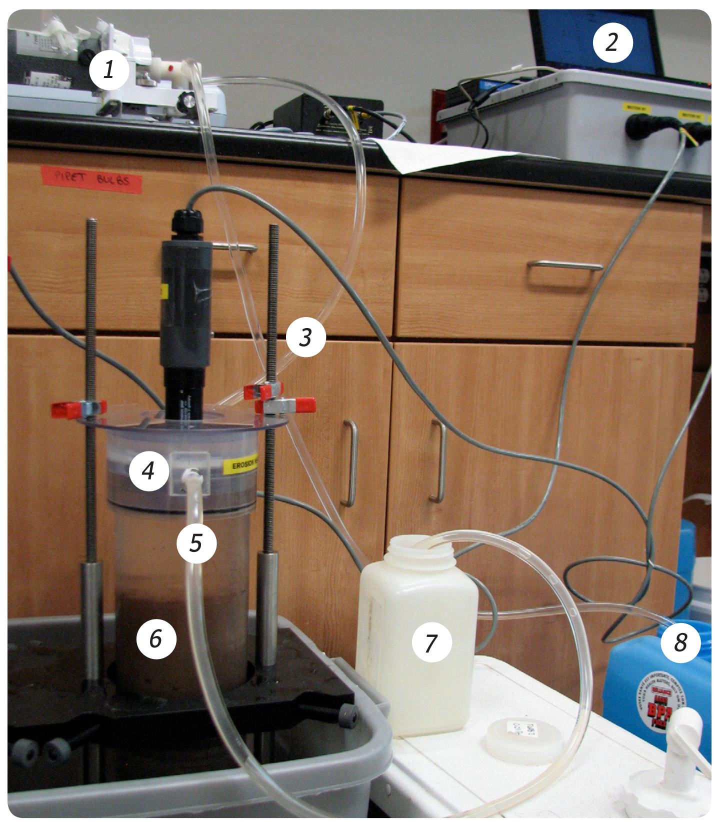
To a sedimentologist, the answer is no, mud is different from sand because it is sticky. The words “mud” and “sand” are used to refer to various size classes of sediment, a term that includes all bits of rocks and minerals that were moved by water at one point. The term mud includes both clay-sized (1 - 4 μm) and silt-sized (4 - 63 μm) grains; sand grains can be as large as 2 mm. It is the small grains of mud that make it sticky. When considering that the human eye requires a gap of approximately 50 μm to perceive two dots as being disconnected, this means that most mud grains cannot be individually resolved without the aid of microscopes.

Microscopes were among the first tools that enabled scientists to look at the grain size distribution of sediment samples, which is part of the work I do. Using a microscope, however, is very time consuming and something I do not particularly enjoy because sediment grains have to be measured and cataloged one by one. Fortunately, scientists now have access to multiple instruments to determine sediment sizes more efficiently. As part of my research, I use a Coulter Counter to obtain the size distribution of mud samples. This instrument relies on volume displacement to infer particle size.

The Coulter Counter

To obtain grain size distributions of sediment samples using a Coulter Counter, the samples need to be suspended in an electrically conductive fluid, called an electrolyte, because the instrument uses an electrical signal to measure particle sizes. More precisely, an electrical current flows from an electrode located in the sample suspension, contained in a beaker, to a second electrode found within a glass tube. At the bottom of the glass tube there is a small hole, called the aperture which allows for the current to flow between the two electrodes. The aperture must therefore be submerged in the sample beaker. As the instrument draws some of the sample suspension into the glass tube, particles are carried through the aperture where they impede the flow of the electrical current. The instrument is designed to maintain a constant electric current between electrodes, and it overcomes the electrical impedance caused by particles by increasing voltage. Interestingly, the required increase in voltage is proportional to particle volume, and this relationship allows the volume of the particles in our samples to be calculated.

In our lab, we add salt to distilled water to create our electrolyte. Before using the electrolyte, however, we filter it using a 0.45 μm filter



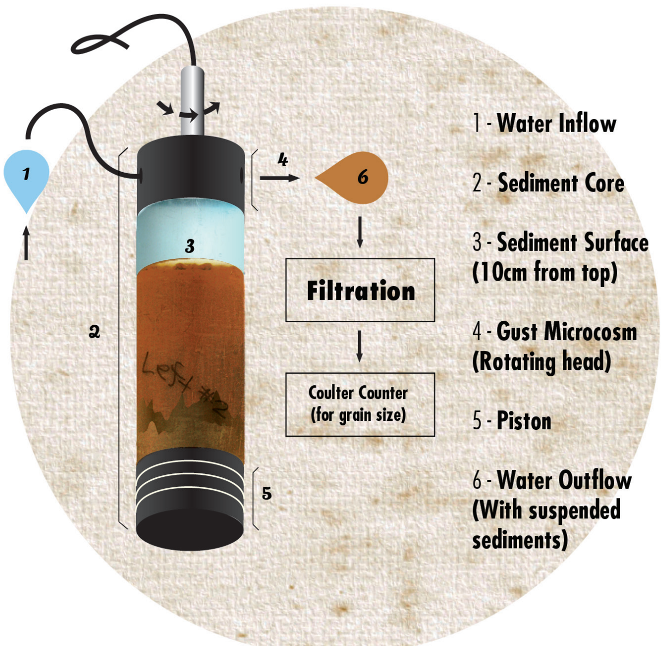
Gust erosion microcosm setup: (1) pump (controlled electronically), (2) computer program controlling pumping and rotation rate, (3) water inflow, (4) rotating head, (5) water outflow, (6) core, (7) sample bottle collecting resuspended sediment and (8) water without sediment.

“The Bay of Fundy is located in Eastern Canada and experiences the highest tides in the world.”

to remove any suspended particles that should not be included in our measurements. The 0.45-μm threshold corresponds to the practical distinction between dissolved and particulate matter. The movement of particles below this threshold, when suspended in water, is dominated by Brownian motion rather than settling. Since Brownian motion is random, studying the size distribution of such small particles will not help us understand the conditions under which they were deposited.

Immediately before running our samples through the Coulter Counter, we submit our electrolyte and sediment to powerful ultrasonic waves to break up any aggregates that formed when sediment grains collided and stuck to each other. Since most of our measurements come from dried samples, the aggregates that form during the drying process are in no way representative of *in situ* conditions and it is therefore more appropriate to look at individual sediment grains. For lack of precise knowledge about the natural packaging of sediment grains, researchers usually study the association between disaggregated grain size

Dr. Paul Hill and Jessica collecting a sediment core



Core collected where the biofilm can be seen peeling off from the sediment surface.

distributions and sediment behaviour. It has been found, for instance, that the smallest mud grains always aggregate in salt water, and thus their size distribution reflects the source of the sediment more so than the local conditions where they settled.

My research

As part of my research, sediment samples from a mud flat in the Bay of Fundy were collected biweekly from April through November 2012, using plastic core tubes. The Bay of Fundy is located in Eastern Canada and experiences the highest tides in the world. Since our samples come from a mud flat, however, we know that the local waters can reach low energy levels because mud grains usually deposit in calm waters. After bringing the samples back to the lab, we simulate natural erosion using a Gust erosion microcosm as shown above. In short, the Gust microcosm is a device that applies a stress to the sediment surface by rotating a disk fitted on top of the cores. Because the rotation rate is controlled, we know precisely the stress experienced by the sediment surface. Throughout the erosion experiment, water flows in and out of the Gust microcosm. The water flowing in contains little to no sediment, but the water flowing out carries with it the sediment resuspended by erosion. I can then filter the output to look at the grain size distribution of the eroded sediment.

“Quantifying perturbation thresholds is particularly important in the Bay of Fundy, as engineers wish to install tidal turbines that could significantly modify the flow regime”

Of course, one should expect that the more powerful the erosion, the larger the sediment grains eroded, so why should this be studied any further? The truth is that natural conditions vary from one environment to the other. Sometimes the sediment was deposited very recently and did not have any time to consolidate, so sediment grains are more easily eroded, and vice versa. In my case, I am looking at the seasonal cycle in the grain size distribution of eroded sediment. Microorganisms living at the sediment surface form sticky biofilms that tend to glue down sediment grains, and my goal is to investigate if some grain sizes are preferentially retained. Given that microorganisms are more abundant in the summer, we expect to observe a seasonal cycle in the resuspended sediment grain size distributions. My most recent results indicate that biofilms in muddy environments retain clays, while biofilms in silty sand environments retain silts. This has direct consequences on seabed texture, as it implies microorganisms can help maintain the current substrate conditions. In fact, if organisms found in finer (coarser) sediment environments retain finer (coarser) particles, we can expect these environments to be in somewhat of a stable state, and thus be resilient to small perturbations.

Quantifying perturbation thresholds is particularly important in the Bay of Fundy, as engineers wish to install tidal turbines that could significantly modify the flow regime.

Why is sediment size so important?

The amount of resuspended sediment has an obvious effect on the amount of light that penetrates the water column, but what about grain size? Smaller particles are known to scatter more light than large particles for the same unit of mass. This means that particle size distribution in the water column can affect the vision of predatory fish and the amount of light that reaches photosynthetic organisms in the water and on the sea floor. Smaller particles also have a greater surface area to volume ratio, which means that, for a fixed volume of sediment, more contaminants can adhere to the surface of small sediment grains than to the surface of large ones. Understanding fine sediment transport in the water system can therefore help predict where contaminant loads will be the greatest. Finally, some organisms are adapted to muddy environments, while others thrive in sandy ones. Understanding the hydrodynamics of an environment and sediment behaviour allows us to predict how changes to the hydrodynamics might affect sediment distribution, and thus species distributions as well.

THIS RESEARCH WAS SUPPORTED BY A NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC) GRANT AND THE OFFSHORE ENERGY RESEARCH ASSOCIATION.

Jessica Carrière-Garwood

In Grade 10, Jessica already had her mind set on a career in ocean sciences, despite never having seen the ocean. After watching a documentary on corals, she realized that she had a keen interest in the field, and the day she caught herself being fascinated by a documentary on mud worms in ocean sediments, she was convinced. In 2009, Jessica rekindled her passion for mud when she joined Dr. Hill's lab at Dalhousie University. In turns, she worked as a research assistant, completed a Combined Honours BSc in Marine Biology and Oceanography, and is currently working on her MSc in Geological Oceanography. Oceanography is the perfect field for Jessica as it allows her to spend time outdoors and travel while working on real world problems. Most recently, she joined a research expedition in the western equatorial Pacific.

Extracting Energy From the World's Largest Bathtub

Making flow measurements to assess the tidal energy resource in Digby Neck, Nova Scotia

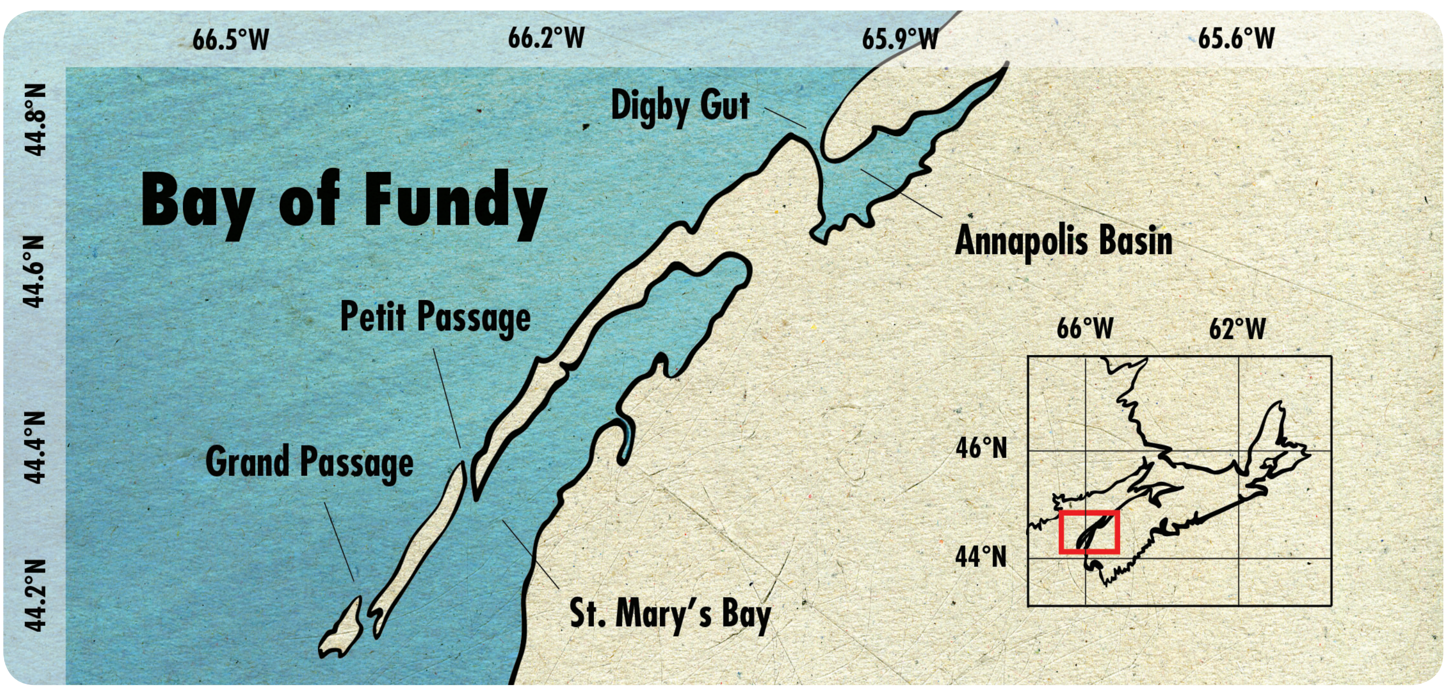
Justine McMillan

Fog hangs over Grand Passage as we head out on the *MS Expectations XL*, a lobster fishing boat based out of Westport, Nova Scotia. Today, however, we will not be catching a single lobster; instead, we are deploying five instruments that measure the speed of the current. The purpose of doing so is that a tidal turbine may be installed here within the next two years. We need to know exactly how fast the water moves so we can estimate how much power a turbine can generate.

The currents in the passage are very strong, which makes our work difficult. We need to deploy our devices during slack water, which occurs between the outgoing (ebb) and incoming (flood) tides. We typically have about 30 minutes to complete our work, and on this particular day we manage to lower three out of five instruments to the sea floor. We must then return to the wharf and wait six hours until the next slack tide. It is a long time to wait, but it gives us a chance to relax and enjoy brunch at the local diner!

What makes the flow so fast?

In addition to assessing the tidal energy in Grand Passage, we are making measurements in Petit Passage and Digby Gut. All three channels are located at the mouth of the Bay of Fundy, which has the world's highest tides. Tides occur in all coastal regions and are caused by the combination of the gravitational forces of the Moon and the Sun, as well as the rotation of the Earth. Compared to other regions, the Bay of Fundy is unique because the depth and length of the bay allow it to



The Digby Neck region, highlighted by the red box in the inset, is located at the mouth of the Bay of Fundy in Nova Scotia, Canada. Measurements of the current speeds were made in Grand Passage, Petit Passage and Digby Gut.

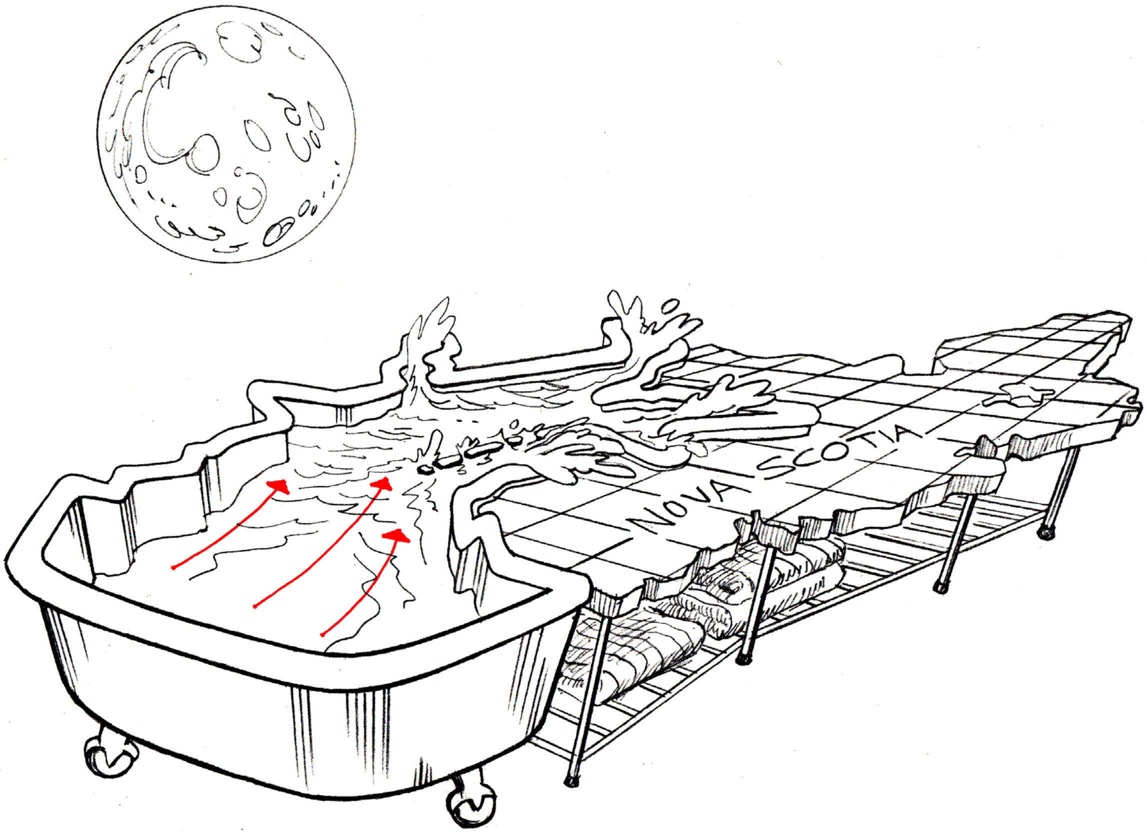


Illustration by David Cullen, Quinline Graphics, 2013

resonate with the gravitational forcing of the Moon. This phenomenon is analogous to creating a wave in the bathtub as a child: if you push the water at just the right frequency, the waves become large enough to spill over the side. So, you can think of the Bay of Fundy as a huge bathtub where the water is "pushed", or more accurately, "pulled", by the Moon's gravity.

At the head of the bay, the high tide water level is about 15 metres higher than the low tide level. For such a large difference to occur, several billion tonnes of water rush in and out on the flood and ebb tides. In fact, the total volume of water flowing through the bay every 12 hours is greater than that contained in all the rivers of the world! When this water encounters a narrow passage, it gets constricted, and thus, must speed up to get through to the other side.

Why is the speed of the flow important?

The types of turbines that are being considered in these passages are called "in-stream turbines" because they extract energy directly from the flowing water. In essence, these devices act similarly to wind turbines except they are mounted on the ocean floor. The advantage of a tidal turbine over a wind turbine is that water is 1000 times heavier than air, which means that a tidal turbine can generate more power from slower flows. To put it into perspective, the flow in Grand Passage typically reaches 2.8 m/s, which is approximately equal to 10 km/hr.

A picture of the ADCP prior to being lowered to the sea bed. The ADCP has four red transducers and is located in the centre of the frame. The recovery floats are contained within the green cylinders.

A wind speed of 100 km/hr would be required to generate the same amount of power!

Another advantage of tidal energy is that tidal flows are somewhat predictable. The gravitational forces of the Moon and the Sun, as well as the rotation of the Earth, are all well described. Based on the position of the Moon, Sun and Earth within their respective orbits, the strength of each of these forcing components or constituents can be estimated. At certain times during the year, the constituents reinforce each other, generating very strong tides. At other times, the constituents counteract each other, resulting in weaker tides.

Although the tidal component of the currents can be predicted, the flow is also controlled by the local coastline and water depth. The effects of these geometric constraints are less well-known and vary significantly over small distances within the passage. We hope that our measurements will allow us to better understand the relative importance of the tidal strength and the geometric constraints, which will in turn allow us to make better predictions of the flow. An accurate estimate of the current speed is extremely important. The power of the flow is proportional to the speed cubed which means that a doubling of the flow speed results in eight times the power! Thus, reliable current measurements are needed so that turbine developers can adequately design their devices for these energetic conditions.

How do we measure the current speed?

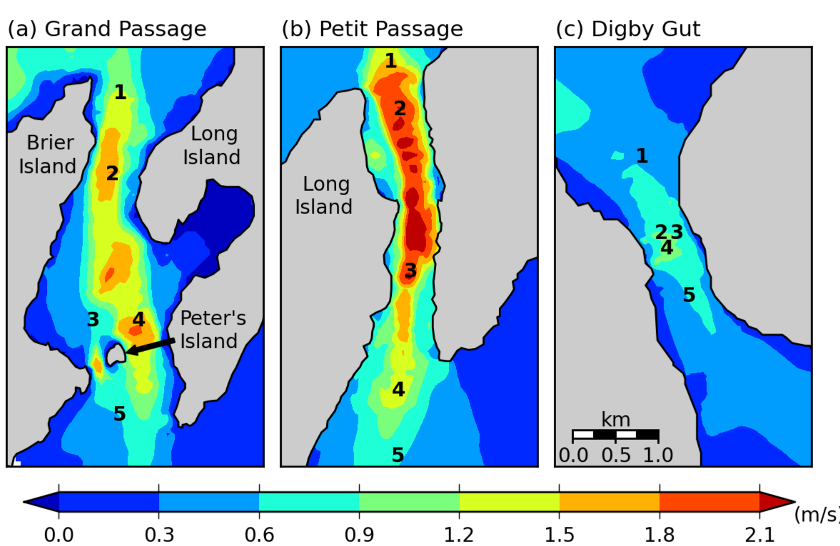
The instruments we use to measure currents are called acoustic Doppler current profilers (ADCPs). They work by sending out a pulse of sound at a known frequency. This signal then reflects off a particle (a small organism or a grain of sand) in the water column and an echo is sent back to the ADCP. Because the particle is moving with the water, the frequency of the returned signal is different than that of the initial signal. By determining the change in frequency, the speed of the particle can be calculated. Essentially, if the particle is moving towards the ADCP, the frequency of the return signal will be greater than that of the initial signal. On the other hand, if the particle is moving away from the ADCP, the returned signal will have a lower frequency. This principle is known as the Doppler shift and is analogous with the change in pitch of a moving ambulance. If an ambulance is moving towards you, the pitch of its siren increases. After it passes you, its pitch decreases due to a decrease in the observed frequency.

What do I do with the data?

About a month after we deploy the instruments, we retrieve them by sending an acoustic signal to a receiver mounted on the ADCP frame. This signal causes a small wire to burn, which in turn, releases a buoy and a recovery line. Once the buoy rises to the surface, we pull the ADCP and its frame onto the boat. The ADCP is then connected to a computer and the data is downloaded.

The objective of the data analysis is to answer questions such as: How fast is the flow? Is the inflow stronger than the outflow? Does the direction of the flow vary between the ebb and flood tides? Is there a large vertical velocity? Due to variations in water depth and coastline geometry, the answers for each site are different. At some sites there is even evidence of sudden bursts of speed. These large fluctuations are of particular interest to tidal turbine developers, who want to be certain that their devices can survive these high-energy events.

Using the flow measurements, I can also estimate how well a specific turbine will perform at a given location. This depends on parameters such as the turbine's size, its electrical efficiency and whether or not it can swivel to face the direction of the flow. Based on the characteristics of the flow at a specific site, an optimal turbine design can be selected. One of the major drawbacks of the flow measurements is that we only gather data at five positions in the entire passage. It is quite possible



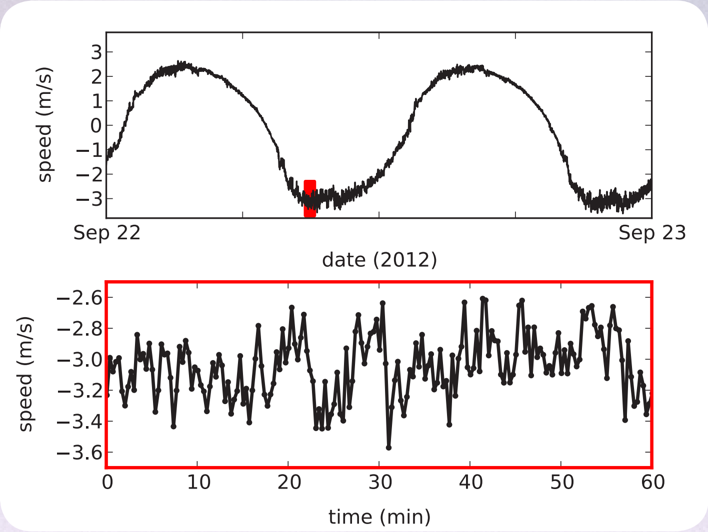
The mean current speed as computed by a numerical model.
The numbers indicate the positions of the ADCPs.

that the flow is faster 50 meter away from where we placed our instrument. To tackle this problem, we use numerical simulations to estimate flow speed and direction throughout the passage. This technique requires many assumptions and approximations, however, we can use our ADCP measurements to validate the model simulations. By looking at the model output, we can select sites where the predicted power is the highest. Then, we can deploy additional ADCPs at these exact locations to verify the model predictions.

What else do we need to know?

Unfortunately it isn't only the speed of the water that is important when considering a location for a tidal turbine. We also need to consider the water depth, the sediment texture, the shipping traffic and even the potential risk for marine species such as whales. We plan to address many of these questions in the next few years, which means that there will be many more foggy days on the *MS Expectations XL* before a tidal turbine is installed.

THIS WORK WAS FUNDING BY THE NATURAL SCIENCE AND ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC) AND THE OFFSHORE ENERGY RESEARCH ASSOCIATION (OERA) OF NOVA SCOTIA.



Depth-averaged speed over a one-day period at Petit Passage Site #4 (top panel). Positive speed values indicate the magnitude of the current during the flood tide and negative speeds correspond to the ebb tide. The lower panel zooms in on a one-hour interval during the flood tide and highlights large fluctuations on short time scales.

Justine McMillan

As a native of Nova Scotia, Justine McMillan has visited the Bay of Fundy many times. She has always been fascinated by the huge tidal range and the glorious mud, but did not expect to be thinking about it on a daily basis. Justine first modelled the tides during a summer research project during her undergrad at Acadia University. After completing her BSc in Physics, Justine ventured west to the University of Alberta to learn more about fluid dynamics and internal waves. But her interest in the harnessing of energy from the Bay of Fundy pulled her back to Nova Scotia, where she began her PhD at Dalhousie University in 2011 with Dr. Alexander Hay. When Justine is not in her office, she can usually be found running, biking or swimming, or putting all three together by racing in triathlons.

A Stirring Story

How turbulence and mixing is caused by shoaling internal waves

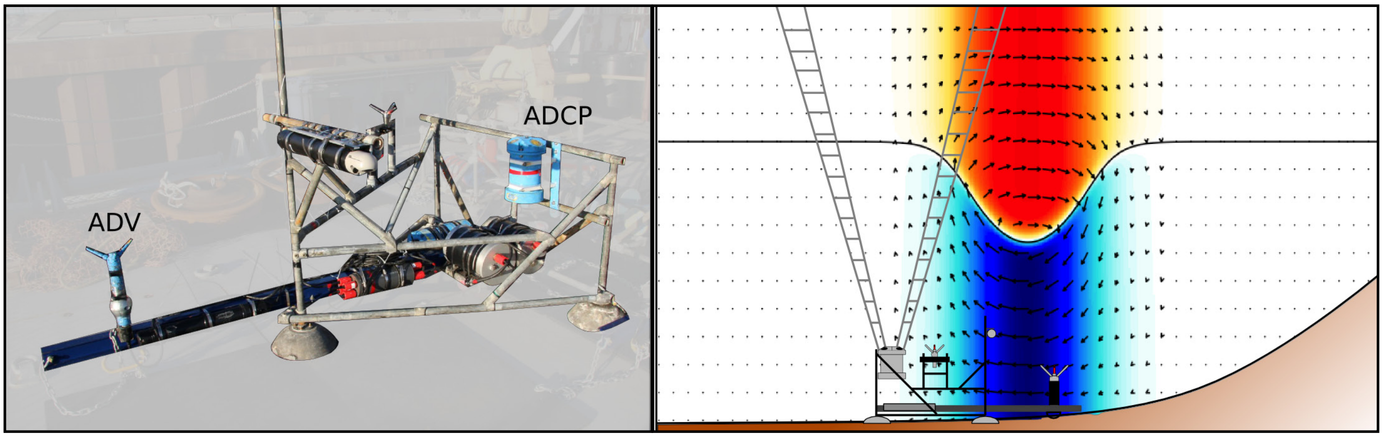
Clark Richards

Introduction

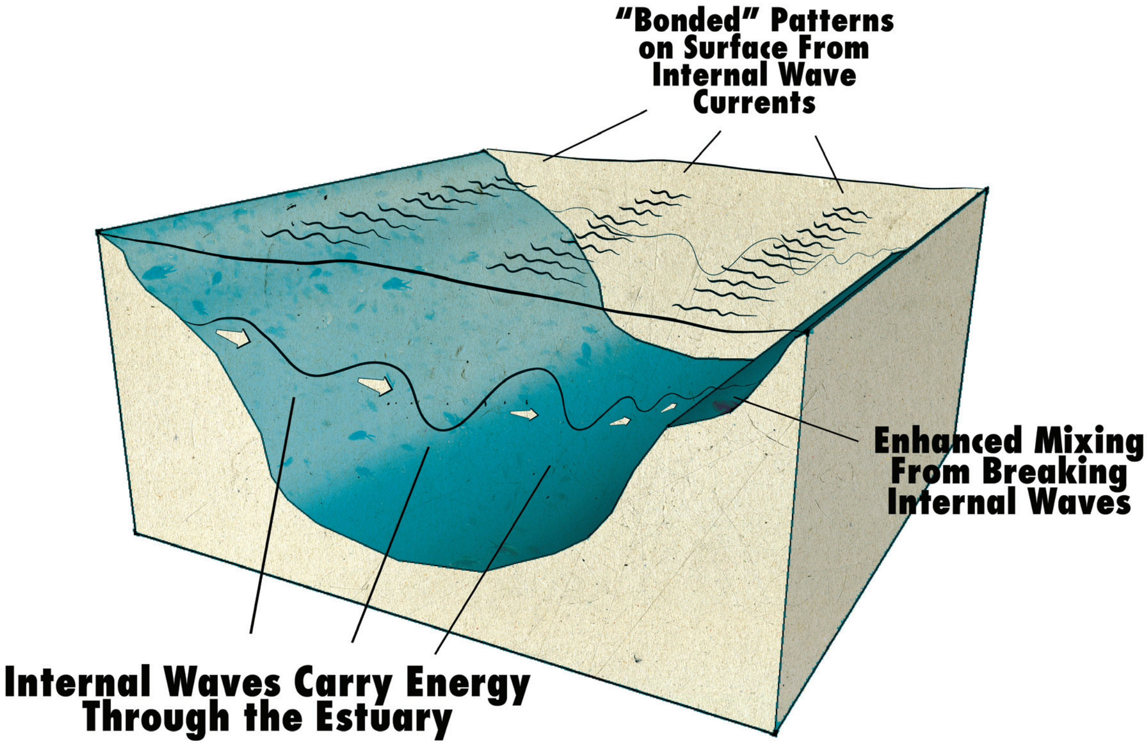
Anyone who has ever visited a beach will be familiar with ocean waves. Waves are a ubiquitous feature on the surface of any large body of water, and they carry energy away from a source (wind, a moving ship or an earthquake) to a location where the energy may be dissipated (breaking waves on a beach). As a result, the study of water waves and their role in physical oceanography remains a topic of active research.

In the ocean, below the familiar surface that we are all accustomed to, the water is typically organized in layers of different density, with lighter fluid resting on top of heavier fluid, like oil floating over water. This layering is often referred to as stratification. The variation in water density occurs because colder or saltier water is denser than warmer or fresher water. Often, in the deep ocean, the transition between layers is smooth and the density profile is said to be continuous. However, in the coastal ocean, including estuaries, the confluence of freshwater from rivers and salty water from the ocean creates a "two-layer" structure, where the density contrast between the layers occurs over a very small vertical distance. In both cases, the layering of density allows for the existence of waves, called internal waves which behave similarly to their surface counterparts in that they can redistribute energy through propagation.

Since coastal internal waves travel on the interface between different density layers, much of the recent interest in them has focused on how they may act to mix the layers together. One can picture a scenario similar to a surface wave breaking on a beach, but instead of the immiscible air and water the wave propagates through two layers of slightly different salinity. Recalling the formation of bubbles, turbulence, and foam by breaking surface waves, it is easy to imagine that these chaotic breaking processes will stir the two layers together and cause them to mix as waves overturn.
Mixing in the ocean is important for all branches of oceanography.



An example SLEIWEX mooring for measuring internal waves. Left: A photograph of one of the moorings on the deck of the R.V. Coriolis II, prior to deployment. Right: A cartoon of the mooring deployed on the bottom as an internal wave passes by. The colours represent the horizontal velocity field of the wave, with red indicating flow to the right and blue flow to the left (the 2D velocities are shown by the arrows). The solid black lines show the density interface between the upper and lower layers. The lines emanating from the ADCP show the sampling pattern of the instrument.



It redistributes human waste and controls the supply of nutrients to near-surface waters. More broadly, patterns of mixing can affect global ocean circulation, which is a critical component of the climate system of our planet. Owing to the relatively small scale of internal waves and their associated turbulent mixing, a better understanding of the processes involved is required if the effects are to be included in numerical models.

SLEIWEX 2008 Field Program

Away from the deep sea, coastal regions represent the first clash between fresh and salt water, which will ultimately mix before spreading out into the open ocean. The role internal waves may play in such mixing is increasingly being recognized, and it was with this goal in mind that the St. Lawrence Estuary Internal Wave Experiment (SLEIWEX) was formed. In June and July 2008 a large field program, jointly funded by CFCAS and NSERC, was launched. It involved ship-based sampling, mooring deployment, and shore-based photography of the sea surface (under the right light conditions, internal waves can have signatures at the surface through changes in roughness patterns).

Acoustic "imaging" of passing internal waves

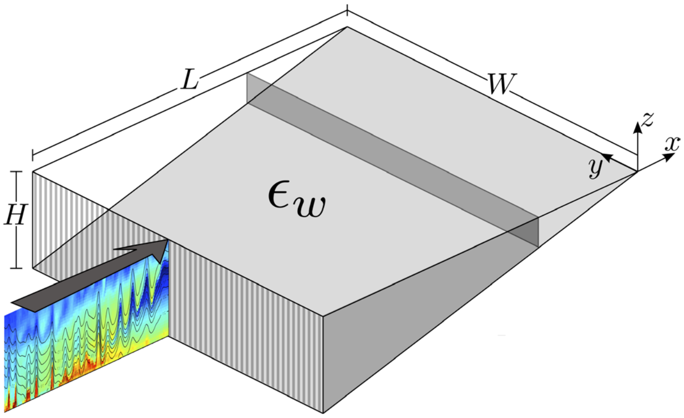
Among the suite of sensors deployed on the moorings, the most important were the acoustic Doppler current profilers (ADCPs). An ADCP measures the Doppler shift of sound scattering off small particles that are assumed to be drifting with the water velocity. By combining the measured shifts from each of four acoustic "beams" pointed in different directions, a three dimensional profile of water velocity can be determined.

Using wave-induced velocities, an estimate of the kinetic energy of the wave can be obtained. To estimate the total energy of the wave, a measurement of the potential energy must also be made. Much like the potential energy of a ball is raised when it is lifted upwards under gravity, the potential energy of an internal wave results from the vertical displacement of fluids of different densities. As sampling the vertical structure *in situ* is too difficult to do rapidly enough to measure the potential energy, I developed a method for inferring the wave-heaved density field from the velocity measurements themselves.

Measurements of turbulence

Turbulence (specifically the rate of dissipation of turbulent kinetic energy) was measured using an acoustic Doppler velocimeter (ADV). The ADV rapidly samples the three-dimensional water velocity at a single point, rather than over a profile like an ADCP. By fitting spectra of the velocity fluctuations to the "universal form" proposed over 70 years ago by A.N. Kolmogorov, a time series of the turbulence level at the mooring was obtained.

Turbulence measured by the ADV is not necessarily caused by internal waves. In fact, the strong tidal currents in the St. Lawrence Estuary are responsible for large amounts of turbulence during the periodic ebb



A simple box model for internal-wave induced turbulence. Measured internal-wave energy is input into the deep end of the triangular box, which has dimensions of H, L, and W. Assuming all the energy is dissipated as turbulence permits an estimate of the dissipation rate associated with the shoaling internal waves.

and flood tides, due to the frictional effects of water flowing over the bottom. To separate the two sources of turbulence, a simple model for "tidal" dissipation was developed (based on energy considerations, the tidal dissipation is proportional to the cube of the water velocity).

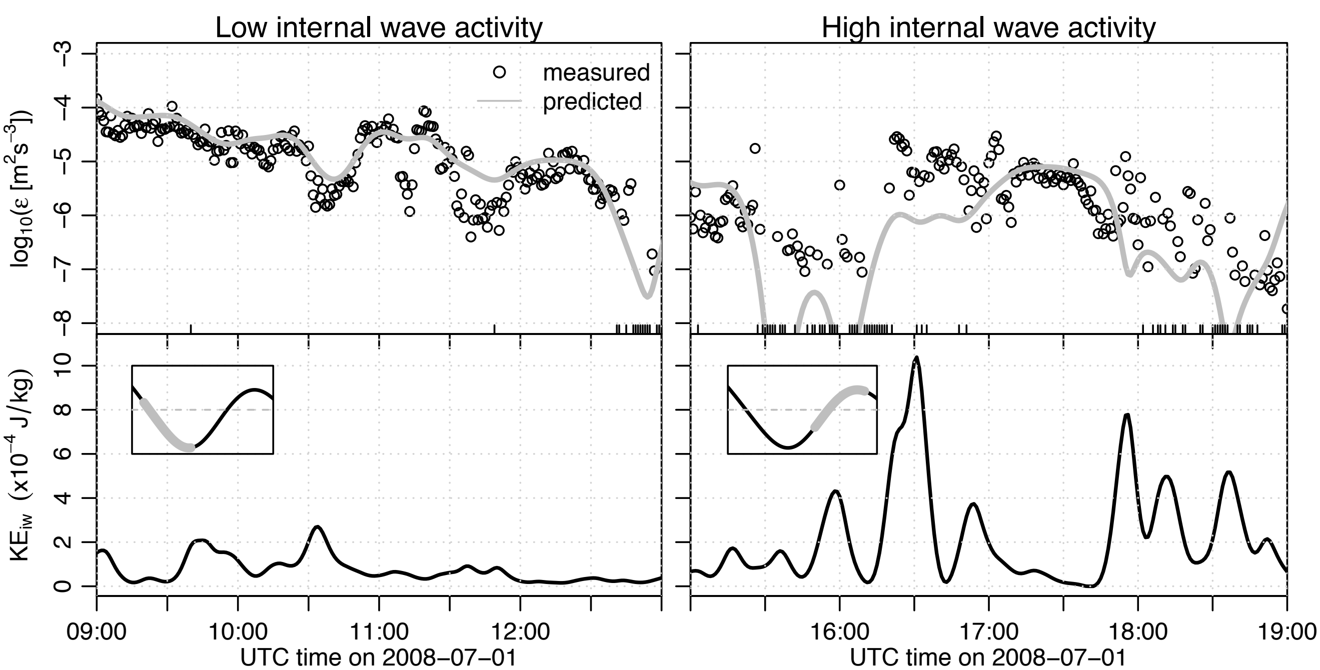
Turbulence from internal waves

During times when internal waves were present at a mooring, the measured turbulence was an order of magnitude larger than would be predicted by the tidal currents alone. This suggests that the internal waves may make an important contribution to turbulence levels where they break. Observed internal waves generally appeared during the flood tide, which was a consistent pattern over the duration of the experiment (as well as in previous experiments in the region).

A simple model for internal wave energy conversion to turbulence

Detailed measurements of the full energy field of the internal waves could be reasonably well predicted using a simple proxy based only on the depth-averaged kinetic energy as measured by an ADCP. To predict the amount of turbulence that the waves would create, I developed a simple model whereby all the energy contained in the waves is fed into the triangular "box" formed by the coastline and the sloping bottom. If no energy is reflected back out of the box, the amount of turbulence produced depends on the wave energy and the cross-sectional area.

By plotting the predicted and measured turbulence as a function of tidal phase, the combined statistics of each tidal cycle allow for a comparison of how well the box model predicts the observed values. The tidal model for turbulence agrees with the measurements only during the ebb tide, when internal waves are not present. Combining the tidal model with the box model produces an estimate of dissipation that matches the



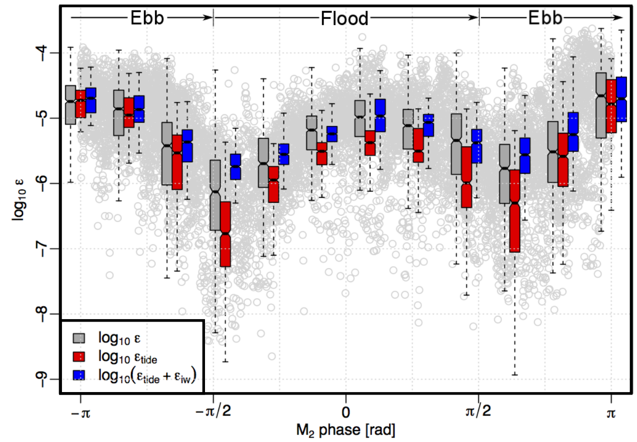
Measurements of turbulence and internal waves on July 1, 2008. Left: During a period when internal wave energy is low (estimated using a time series of the kinetic energy, KE), the measured turbulent dissipation (black dots) closely matches that predicted by a tidal model (grey line). Right: When shoaling internal waves are present, the measured dissipation rates were as much as a factor of 10 larger than would be expected based only on the tidal flow (note the logarithmic scale for the dissipation rates).

observations during both the peak ebb and flood phases, suggesting that the inclusion of internal waves is required to capture all of the turbulence in this location.

Summary

These results are significant, as they indicate that in order to accurately represent regions such as the St. Lawrence in a numerical model, internal wave processes should be included. Directly including wave processes and turbulence is not feasible because of the small spatial scales involved, and so parameterizations of the waves will have to be developed to permit their inclusion in numerical models. The results presented here suggest some avenues for future parameterizations, based on the wave energetics, but there is still much to be done. Following the example of surface waves, a complete "wave lifetime" model that follows the energy pathway of the waves from generation to dissipation will likely have to be constructed.

THIS RESEARCH WAS SUPPORTED BY A NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC) GRANT AND THE CANADIAN FOUNDATION FOR CLIMATE AND ATMOSPHERIC SCIENCE (CFCAS), THE KILLAM TRUSTS AND THE DEPARTMENT OF FISHERIES AND OCEANS CANADA (DFO).



A simple box model for internal-wave induced turbulence. Grey boxes = measurements, Red boxes = tidal model, Blue boxes = tidal model combined with box model

Clark Richards

Born in North York, Ontario, Clark spent most of his life living in Atlantic Canada, attending the University of New Brunswick (BSc), Memorial University (MSc), and Dalhousie University (PhD). After completing his undergrad in physics, with a focus on quantum mechanics and laser spectroscopy, he was drawn to physical oceanography by the prospect of actually being able to work outdoors (at least once in a while), and has never looked back. His PhD work at Dalhousie, supervised by Dr. Dan Kelley, focused on measurements of internal waves and turbulence in the St. Lawrence Estuary. In Fall 2012, he began a postdoc at the Woods Hole Oceanographic Institution, working with Dr. Fiamma Straneo on the transformation of Atlantic waters in the Nordic Seas and on the interactions between the ocean and marine terminating glaciers in Greenland.

Chalk It Up to Bubbles?

Investigating the impacts of wind-generated bubbles on optical estimates of calcite in the Southern Ocean

Michael Brown

Ocean colour

The research I am conducting for my MSc is in the field of optical oceanography. In a general sense this field involves studying how visible light originating from the Sun interacts with the ocean and its various constituents (phytoplankton, sediments and dissolved matter). Upon entering the ocean, this light is altered as a result of absorption and scattering by these materials, typically in a manner unique to the substance. Therefore, a primary goal of the field is to use the optics of the ocean to remotely infer what is in the water, and how much of it there is. Often this is accomplished simply by looking at the colour of the ocean (ocean colour). For example, chlorophyll, an important pigment that phytoplankton (and all plants) use to photosynthesize, strongly absorbs blue and red light but reflects green light. Therefore blooms of phytoplankton are green in colour, while less productive regions appear bluer. Computational algorithms used to estimate chlorophyll from ocean colour often utilize this fact, and base chlorophyll concentration on a ratio of blue to green light. Of course, algorithms to derive other substances have also been developed. The power of ocean colour as an oceanographic tool becomes readily apparent when you consider that sensors measuring the colour of the ocean have been mounted to satellites, providing scientists with global coverage every day or so. This has made it possible to study remote parts of the ocean, previously inaccessible because of time or money, all from the comfort of one's office. Additionally, ocean colour sensors can be attached to ships, buoys and other observing platforms, further reducing the amount of resources required when compared to manual sampling.

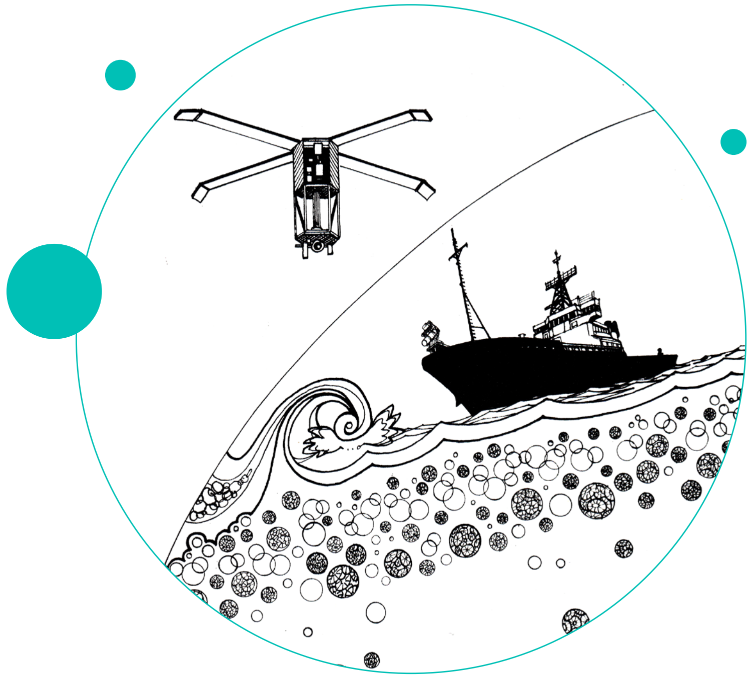
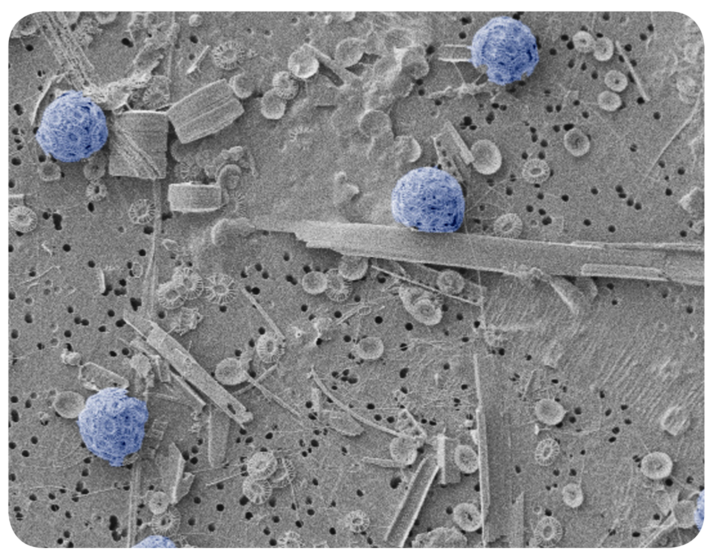


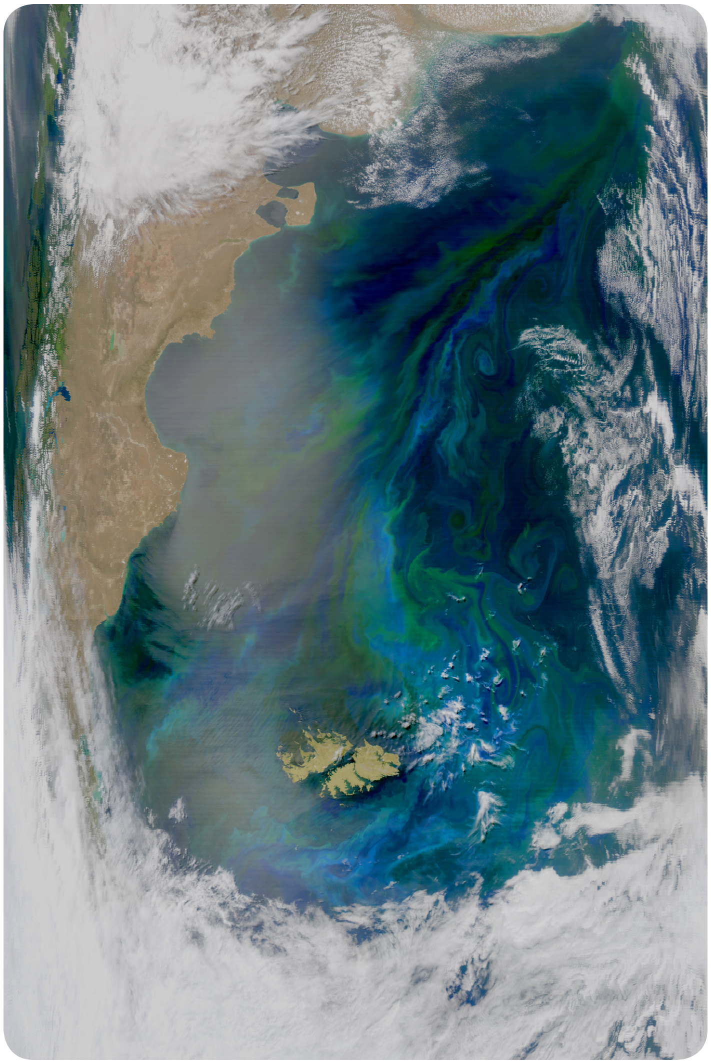
Illustration by David Cullen, Quinline Graphics, 2013

The Great Calcite Belt

Using global imagery of ocean colour measured by satellite, a feature with a unique optical signature has been identified in the Southern Ocean that consistently encircles the globe from ~38ºS to ~60ºS during summers in the Southern Hemisphere. The feature is characterized by elevated reflectance, which is defined as the ratio of the amount of light leaving the ocean to that entering it. This indicates that there is something present in the water scattering light backwards toward the satellite. Indeed, when these reflectances are plugged into ocean colour algorithms that estimate particulate inorganic carbon (PIC), also referred to as calcium carbonate, they yield elevated concentrations.



Scanning electron micrograph of coccolithophores (Emiliania huxleyi), false-coloured blue, that were collected on the Kerguelen Plateau during the 2012 Great Belt Research Cruise. The coccolithophores are dispersed among an assortment of detached coccoliths and other phytoplankton fragments. Photo Credit: Helen Smith (NOC).



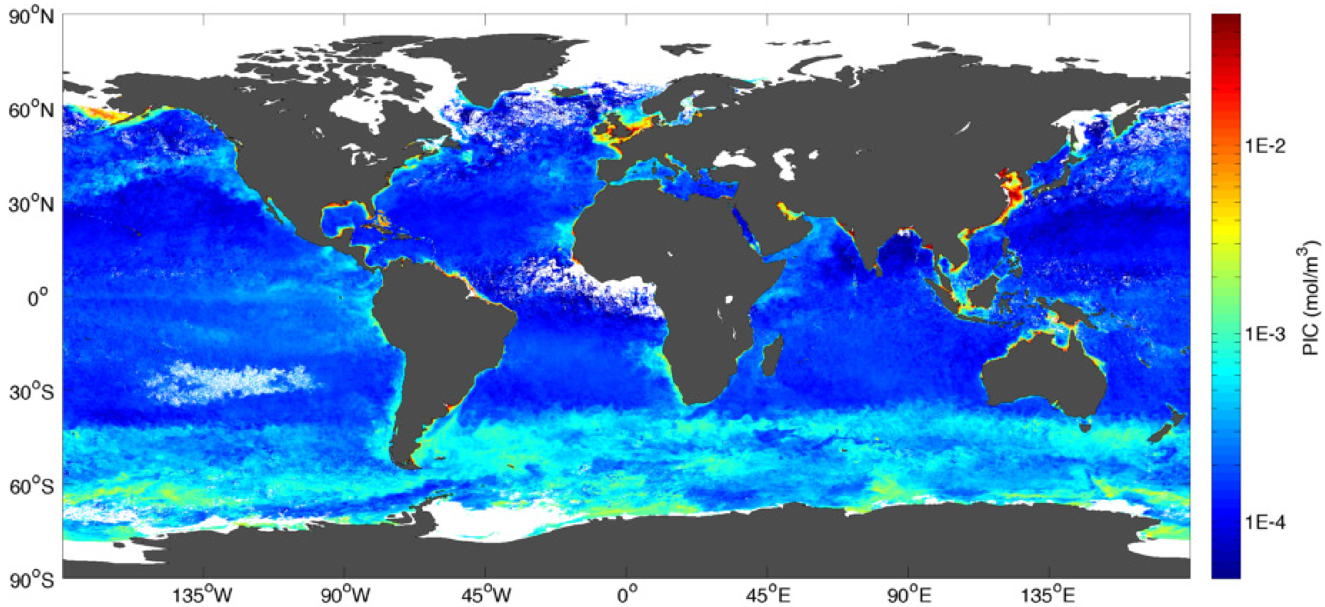
True-colour satellite image (MODIS-Aqua sensor) of the Patagonian Shelf on December 10, 2008. The high reflectance, turquoise-coloured water to the north and encircling the Falkland (Malvinas) Islands indicates the presence of a coccolithophore bloom.
Source Data Credit: NASA/GSFC/OBPG.

These PIC algorithms are designed specifically to estimate calcite (chalk), a form of calcium carbonate. This suggests that this feature in the Southern Ocean is due to the presence of an abundance of coccolithophores, a type of calcifying phytoplankton that surround themselves with intricately shaped calcite plates, or coccoliths. Although tiny, coccoliths are very efficient at backscattering light, and therefore provide coccolithophores with a strong optical signal capable of elevating reflectance. Coccolithophores scatter so much light, in fact, that a bloom will turn the surrounding ocean a characteristic turquoise or "milky-blue" colour, which can be seen by the naked eye and even from space!

Various research expeditions to the Southern Ocean have confirmed that coccolithophores are indeed present in this feature, and thus it has been aptly named the Great Calcite Belt (GCB). With a total area of ~52 x 10^6 km^2, the GCB is likely the largest feature in the world characterized by a high abundance of calcifying phytoplankton. This is a big deal! Coccolithophores are important for a variety of reasons, but a primary one is their role in the global carbon cycle. For example, the production and dissolution of calcite in the ocean can directly impact atmospheric carbon dioxide levels. Specifically, the production of calcite will yield carbon dioxide while the dissolution of calcite will consume it. In addition, sinking calcite is a large source of marine sediments (the White Cliffs of Dover are composed primarily of ancient coccoliths) and can also act as ballast for particulate organic matter. Therefore, calcite can impact the efficiency of the biological pump, which is one of the mechanisms by which atmospheric carbon is sequestered into the ocean's interior. Considering the immense size of the GCB, as well as the calcification rates of coccolithophores, this feature could potentially have significant implications for global climate change and ocean acidification.

Bubbles?

Clearly it is necessary to have accurate ocean colour estimates of calcite produced by coccolithophores, particularly in a feature as potentially important as the GCB. Unfortunately this is not always a simple task. For example, the Southern Ocean is notorious for its high wind speeds. It has therefore been suggested that in addition to coccolithophores, the elevated reflectances observed in the GCB are due to submerged layers of bubbles injected into the upper ocean by breaking waves during periods of strong wind. Bubbles, just like coccolithophores, are very efficient at backscattering light, and it has been demonstrated that they too can significantly increase reflectance. This can be problematic for ocean colour algorithms that estimate calcite. These algorithms function by exploiting the strong backscattering properties of coccolithophores and relating reflectance to calcite concentration. Bubbles provide an additional source of backscattering that can be mistakenly attributed to calcite, and thus result in an overestimation of its concentration.



Seasonal average of satellite-based (MODIS-Aqua sensor) particulate inorganic carbon (PIC) concentrations for the 2008-2009 austral summer. The Great Calcite Belt is visible as the band of elevated concentrations stretching across the Southern Ocean. Source Data Credit: NASA/GSFC/OBPG.

My work

The focus of my research is to determine if wind-generated bubble layers elevate ocean colour estimates of calcite in the GCB. It must be emphasized that this does not preclude the presence of coccolithophores. Indeed, multiple pieces of compelling evidence have been presented that confirm their existence in the GCB. Rather, I assume that bubbles act in combination with coccolithophores to elevate reflectance, thereby resulting in overestimates of calcite. It would be important to determine if this is occurring, since given the large size of the GCB, it could impact estimates of calcification on a global scale.

My research consists of three components, each of which has been designed to approach this problem in a different manner. The focus of the first component is to determine the extent to which bubbles can optically mimic coccolithophores. I use a computer model that computes the backscattering properties of a wind-generated bubble layer as a function of wind speed. Running this model for wind speeds observed in the GCB allows me to compare the model output with backscattering values typical of coccolithophore blooms.

For the second component of my work, I have developed a method to correct ocean colour estimates of calcite for the backscattering effects of co-occurring bubbles. This procedure makes use of the same bubble model, and requires an estimate of the wind speed that was coincident with the ocean colour measurements. I have applied this method to satellite imagery of a coccolithophore bloom that formed in 2008 off the Patagonian Shelf, which is a region in the GCB that is well known for the seasonal occurrence of coccolithophores. Comparison of the calcite imagery before and after the correction allows me to determine if bubbles are introducing significant errors.

A wind-blown Southern Ocean during the 2012 Great Belt Research Cruise.
Heard Island can be seen in the background, covered in snow.

Finally, the goal of the third component of my research is to determine if bubble-enhancement of calcite can be detected with a dataset collected during an oceanographic research cruise that observed the 2008 Patagonian Shelf coccolithophore bloom. This is accomplished by comparing estimates of calcite derived from ship-based ocean colour with more direct measurements and determining if differences between the two are related to wind speed. Together, the above three components combine the use of modeling, satellite and ship-based measurements, to allow me to rigorously approach this problem.

All of my work has benefitted from opportunities to travel to exciting places relevant to my research. Last spring I participated in the 2012 Great Belt Research Cruise, a month-long oceanographic expedition from South Africa to Australia though the Indian Ocean sector of the GCB. This cruise was led by Dr. William Balch, a Senior Research Scientist at Bigelow Laboratory for Ocean Sciences. It is Dr. Balch's research that has led to the development of ocean colour algorithms for calcite, as well as the discovery of the GCB. It is also his Patagonian Shelf dataset that I am using for my work. During the 2012 cruise I assisted his lab in collecting a similar dataset, an experience that was extremely useful for my own research. Additionally, in summer 2012 I completed an internship with the Ocean Biology Processing Group at NASA's Goddard Space Flight Center. This group is responsible for many aspects of various ocean colour satellite missions, and receiving their input on my work was invaluable.

I am very excited to be involved with this research. Optical oceanography is a great field, and coccolithophores are a fascinating subject. The coccoliths they form are tiny and beautifully intricate, yet capable of significantly affecting the optics of the ocean to generate large features that mesmerize when viewed from space. Even more interesting is the ecological and biogeochemical importance of coccolithophores. I find the potential global significance of the GCB with regard to climate change and ocean acidification particularly compelling. Indeed it is the gravity of these topics that originally convinced me to study an environmental science. I consider myself very fortunate to have the opportunity to conduct research that is both interesting and meaningful.

THIS RESEARCH WAS SUPPORTED BY THE CANADIAN HEALTHY OCEANS NETWORK (CHONE), A NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC) STRATEGIC NETWORK. THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA) GODDARD SPACE FLIGHT CENTER (GSFC) SUMMER INTERNSHIP PROGRAM PROVIDED ADDITIONAL FUNDING. THE U.S. NATIONAL SCIENCE FOUNDATION (NSF) SUPPORTED THE COLLECTION OF DR. WILLIAM BALCH'S PATAGONIAN SHELF DATASET UNDER GRANT NO. 0961660.

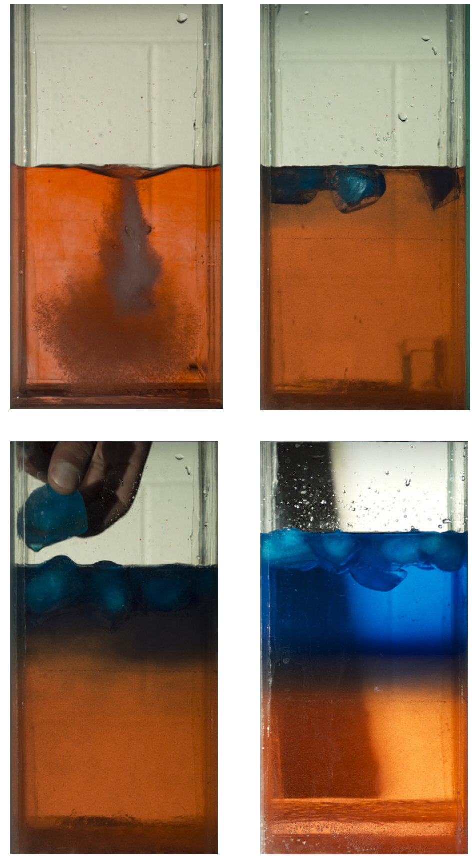
Michael Brown

Mike grew up in New Hampshire and central New York, two areas not known for their expansive coastlines. Although he has always enjoyed science, Mike was initially not sure what specific field to pursue while an undergraduate at Cornell University. However, that decision was easily made after taking an introductory oceanography course. He thoroughly enjoys the multidisciplinary aspect of the field, as well as the ability to travel to exciting places and conduct interesting research. Mike is currently finishing up his MSc at Dalhousie under the supervision of Dr. Jon Grant, and hopes to then pursue a PhD. When not studying, Mike likes to play music and sports, and listen to Tom Petty.

The Curious Case of Bobbing Henry

A simple demonstration of oceanic double diffusive convection

Nicholas Dourado



To set up double diffusive convecting layers, salt is added to water that is heated from the bottom. When ice cubes are placed on the top, the melted water from the ice will not mix with the salty water and layers will begin to form. Photo Credit: Mary Ellen Oxby.

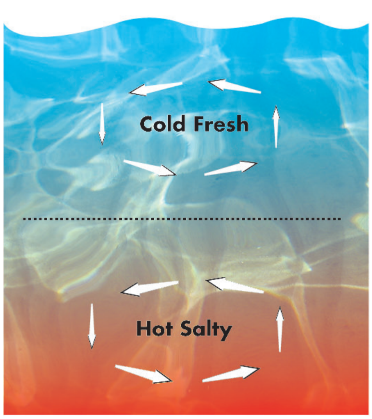
Ghostbusters

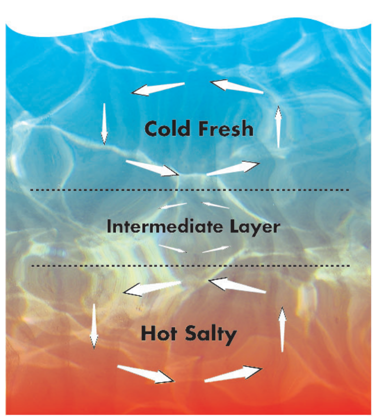
If you can't see something, how can you be sure it's really there? Understanding how heat and energy flow in the atmosphere and ocean is an important part in understanding the behavior of climate systems; however, winds, ocean currents and the movement of heat are like enormous ghosts - undetectable to the naked eye.

Simple laboratory experiments can be used to ask questions about the processes at play in the ocean.

Dr. Barry Ruddick introduced me to a most mysterious sight while I was hoping to gain insight into the stratification of water in the ocean, where a lightweight layer of water can sit on top of heavier deep ocean water and a strong separation between the two is observed.

The mystery concerns the movement of Bobbing Henry, a glass vial who travels through the water column in search of a stable place to rest. Henry is only comfortable when the density of the surrounding fluid will support his weight. Henry, like Goldilocks, prefers conditions that are 'just right'. As his temperature changes, Henry's air-filled innards will expand or contract prompting a change in location. Cold water will make him lethargic and he will fall, while warm water gives him energy, propelling him upwards.

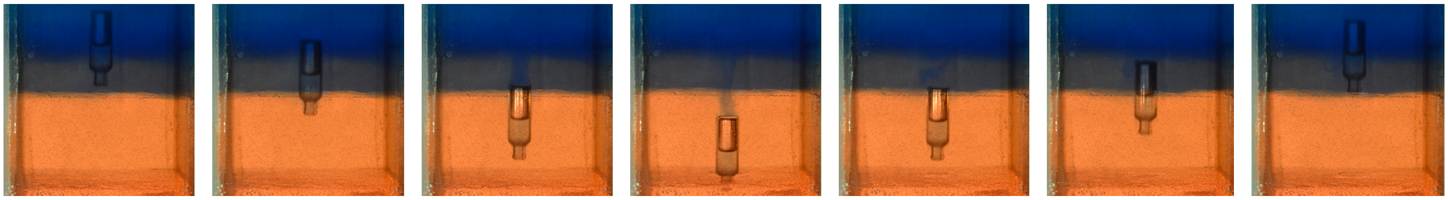




Cold fresh water is heated from the bottom: convection occurs

Warm salty water is cooled from above: convection occurs

The layers do not mix. New layers form as heat and salt diffuse through the interface



The dance of Bobbing Henry. Henry cools in the top layer and falls into the bottom layer where he warms and is propelled back into the cold top layer.
Photo Credit: Mary Ellen Oxby

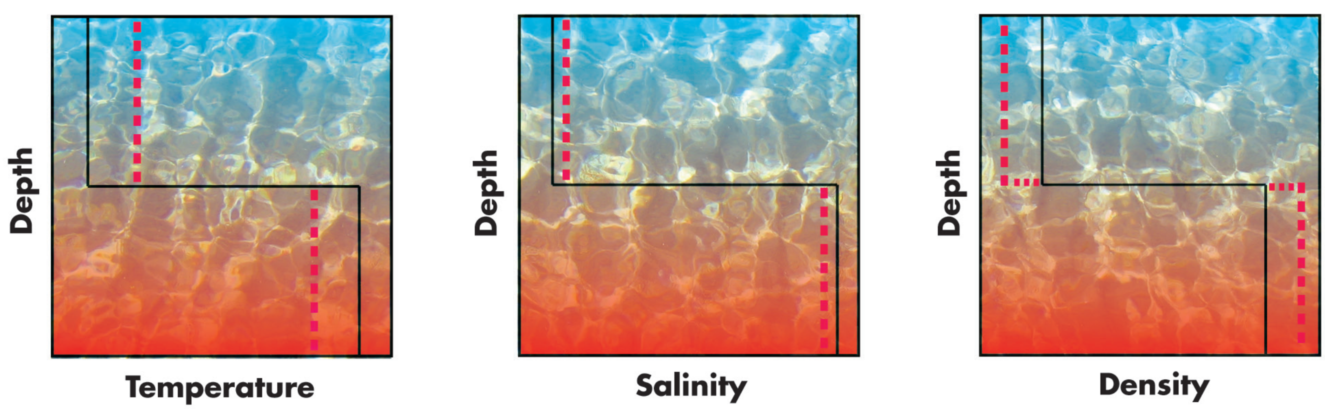
However, Henry can't seem to make up his mind. He wanders restlessly from the lighter top layer to the denser bottom layer. Henry is a type of physical model for a parcel of water, since changes in density and pressure generally govern his movements. Perhaps Henry is jumping up and down because there is something he wants to tell us?

Heat transfer, buoyancy and diffusion

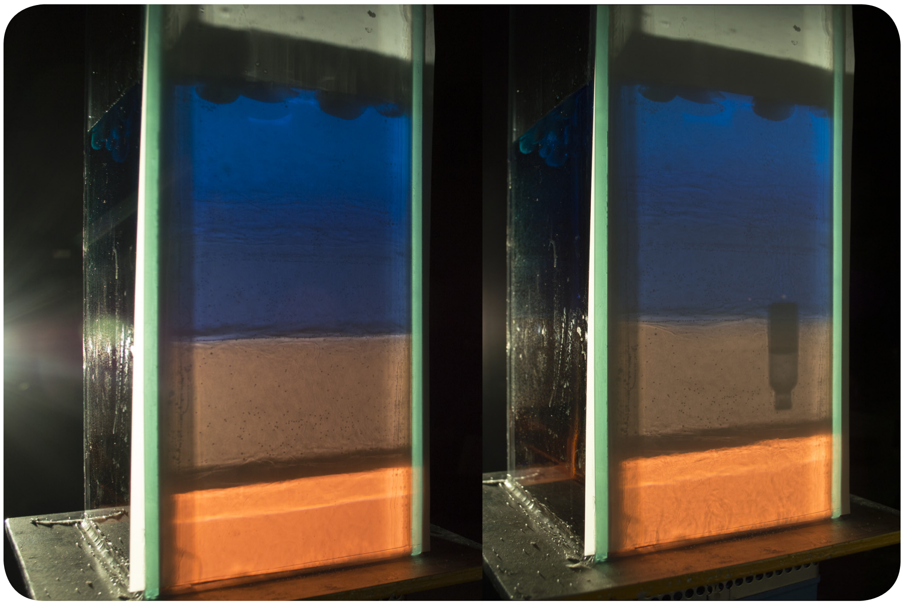
If water is not uniformly dense throughout, less dense water will float on top of more dense water due to the force of buoyancy. Thus, the flow of heat can cause motion in fluids since the addition of heat will cause a parcel of fluid to expand, becoming more buoyant; conversely, as a parcel of water loses heat it will contract, becoming less buoyant. From this it seems that hot water must float on top of cold water, but is this necessarily the case?
Henry seems to tell a different story. As Henry falls into the bottom layer, he is propelled back into the top layer where he again falls into the bottom layer to endlessly dance back and forth. Henry is supplied with the energy from heat in the bottom layer that he loses in the top layer, instigating his descent. Henry is bobbing between water layers that are warmer at the bottom and colder on top!

The missing piece of this puzzle is the contribution to density by dissolved salt, also known as salinity. Salinity makes water more dense, thus deep water is often saltier than surface water. If enough salt is added to warm water, it can be less buoyant than colder fresh water that can stably float on top. Although, to get at the full significance of Henry's dance we must turn our attention to diffusion.

Diffusion acts to reduce differences or gradients and, over long time scales, creates uniform distributions of heat, dissolved matter and density in fluids. Diffusion occurs due to the random motions of particles. Consider a bag of red marbles and a bag of green marbles. Marbles are randomly swapped from one bag to the other. The number of red or green marbles in each bag will mix until both bags contain just about an even number of red and green, after which the exchange will no longer significantly alter the composition in each bag.



Heat will diffuse from the warm layer to the cold, heating the surface layer (dashed line). Salt will flux from the salty bottom layer into the fresh top layer (dashed line). Thus, the gradient of temperature and salinity will decrease. However, the top layer will warm due to the faster diffusion of heat and the top layer will become lighter; the density gradient grows (dashed line)!



As the system evolves, additional layers will form on either side of the first interface. These layers form as heat and salt diffuse through the interface. Photo Credit: Mary Ellen Oxby.

Similar is the exchange of heat and salt; if in contact, hot regions of water will exchange heat with colder regions and saltier regions will exchange salt with fresher regions. In these cases, heat will always move from high temperature to low, and salt from salty to fresh.
Henry's motion results from the combination of heat and salt in the water and their differing effects on buoyancy and rates of exchange by diffusion. Henry's glass membrane will allow heat to diffuse through and alter his inner equilibrium, while salt cannot. In the bottom layer, he will feel the uplifting effects of heat without the stabilizing effect of salinity.

Henry's behaviour does tell us something about water under the influence of changing temperature and salinity. Henry's glass membrane, that restricts the diffusion of salt, is not required for these dynamics to occur. Since heat diffuses so much faster than salt, the movement of salt is inhibited. This shows that heat flow can influence buoyancy well before the effect of salinity becomes apparent. This suggests that cold fresh water on top of warm salty water can resist mixing. If warm bottom water is introduced to the top layer it will cool and fall back into the bottom layer. If cold fresh water falls into the bottom layer it will warm and return to the top.

Peculiar dynamics that arise when fluids that have components with differing rates of diffusion and opposing effects on density are called double diffusive phenomena. Henry Stommel, Arnold Arons and Melvin Stern discovered double diffusive processes in the ocean upon the realization that pipe-like mixing could occur across stably stratified layers that are warm and salty at the surface and colder and fresher at depth. This double diffusive process is known as salt fingering.

Double diffusive processes garner attention due to the unusual density flux that results. Heat will move from hot to cold layers, decreasing the density of the cold layer and salt will move from salty to fresh layers, increasing the density of the fresh layer. The flux of temperature will be greater than the flux of salt and the top layer will become less dense. Where diffusion normally reduces gradients between layers, in double diffusive systems, the density gradient can grow!

Can I take it home, please?

Double diffusive processes can be formed in simple kitchen experiments. Fill a heatproof container with water and mix enough salt so that an excess of salt remains on the bottom of the container. Place the container on a heated element and float ice cubes on the top of this salt water solution.

As the ice cubes melt, the cold water does not mix with the underlying salty water; remarkably, instead a sharp interface begins to evolve between the layers. The lower layer will not exchange fluid with the top layer by convection as may be expected, since the lower layer is so dense that too much energy would be required to mix the fluids. However, heat and salt still flux through this layer due to molecular diffusion and regions around the interface begin to form new layers. Since heat moves faster than salt, the top layer will become lighter and the layers will become more stable.

Case closed?

Generations of oceanographers, including researchers at Dalhousie University such as Drs. Dan Kelley, Barry Ruddick and Dr. Tetjana Ross (my supervisor) have examined double diffusive systems. However, many questions about double diffusive processes, regarding their significance in the movement of heat in the ocean, remain unanswered.

In the Arctic, warm salty water from the Atlantic can become buried under fresh water from melting sea ice. Since it is still difficult to estimate heat fluxes through double diffusive layering in the ocean from laboratory models, it is difficult to know how heat fluxes in the ocean contribute to the melting of ice sheets in polar regions. Understanding double diffusive systems may be a key to probing the mysteries of climate change.

The development of the double diffusion hypothesis demonstrates the value of thought experiments and simple desk-scale models. The element of surprise that arises from imaginative thinking and keen observation is important in navigating the dynamics of complex, interconnected systems.

Don't take my word for it - a counterintuitive system is in your reach. While Henry is not a perfect model of a parcel of water, he shows that complicated physics can be approached in interactive, fun and simple ways. Henry's motto, taken from a key formulator of our understanding of diffusion, Albert Einstein.

"Play is the highest form of research."

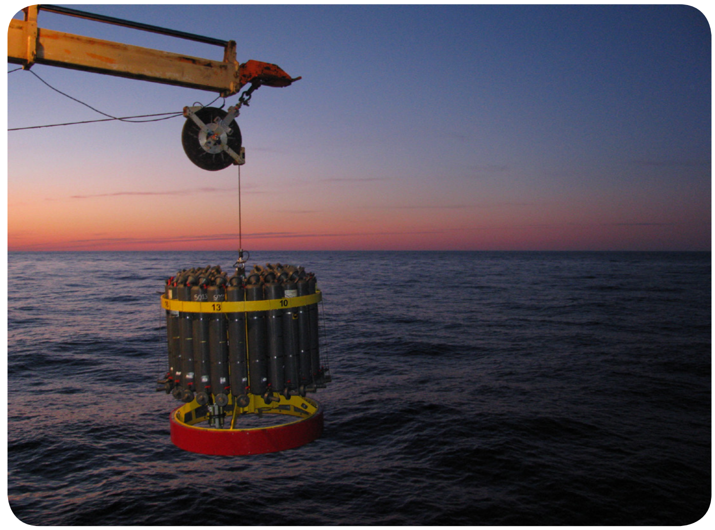
I AM GRATEFUL FOR ASSISTANCE FROM DR. BARRY RUDDICK, DAN KELLEY AND TETJANA ROSS FOR MATERIALS AND IDEAS. FUNDING SUPPORT WAS PROVIDED FROM THE NOVA SCOTIA DEPARTMENT OF ENERGY'S PENGROWTH ENERGY INNOVATION GRANT.

Nicholas Dourado

Nicholas Dourado is an MSc student in Physical Oceanography at Dalhousie University with Dr. Tetjana Ross. Since completing his environmental engineering degree, he has been running around Nova Scotia looking for interesting problems outdoors. He is currently working on using sound energy to detect ice hazards that threaten tidal power developments in the Bay of Fundy, using sound energy. Nicholas likes to play with water, sound and people, rock and roll on ocean waves and read about fluid dynamics while lost in a cup of coffee.

The Radium Stopwatch

Using decaying isotopes to understand marine inputs of a key greenhouse gas



Our sampling "rosette" during a sunset deployment. The rosette has 24 numbered Niskin bottles around the outside, which will be closed at a different depth, providing us with seawater from the surface, all the way down to over 5 km deep.

William Burt

Every April in Nova Scotia, as winter begins to wind down and the leaves begin to reappear, our lab group starts its fieldwork by heading out to sea! Three weeks on the coastal seas of the Canadian North Atlantic Ocean. Sounds idyllic, in fact, we call these research missions "cruises". But April is storm season in the North Atlantic, so our floating onboard laboratory is 'rockin', but not in a good way. Nevertheless, the science team goes about its business. Biologists onboard are after the tiny marine plankton, so they dip their fine-meshed nets into the shallow waters. Meanwhile, physicists are collecting information on ocean currents and circulation. Using remote technology, they retrieve an array of current meters that have been suspended in the ocean collecting data. These current meters are released and float to the surface, where the ship's crew hauls them onboard to extract the data. For the rest of us, the chemists, it's the materials dissolved in the seawater that we're interested in. We drop ultra-thick plastic bottles - made to withstand the extreme pressures of the deep ocean - to a variety of depths, and haul up our seawater samples.

Seawater is considerably more complex than salt and water. When it comes to dissolved material, seawater is like your backyard shed, absolutely packed with interesting things, some of which you never even knew you had! Our lab is searching for two particular items: Carbondioxide (CO_2) and radium isotopes. CO_2 is not hard to find. Thanks to human-related activities like heavy industry, motor vehicles and deforestation practices, there are increasing levels of CO_2 being released into the atmosphere and seeping into the world's oceans every year. In the North Atlantic, all it takes is enough seawater to fill a can of soda pop to get a good detectable level of CO_2.

Our second item of interest is much more difficult to find. In order to find a measurable amount of radium isotopes, we have to collect enough seawater to fill over 500 soda pop cans. Once we extract both of these dissolved materials from a particular water depth in a particular location, we move on and repeat the process.

By the end of the cruise, we have filtered and extracted almost enough seawater to fill a dump truck, and we head home having mapped out a section of ocean with CO_2 and radium concentrations. This information forms one piece of a giant jigsaw puzzle we are trying to put together to increase our understanding of ocean acidification.

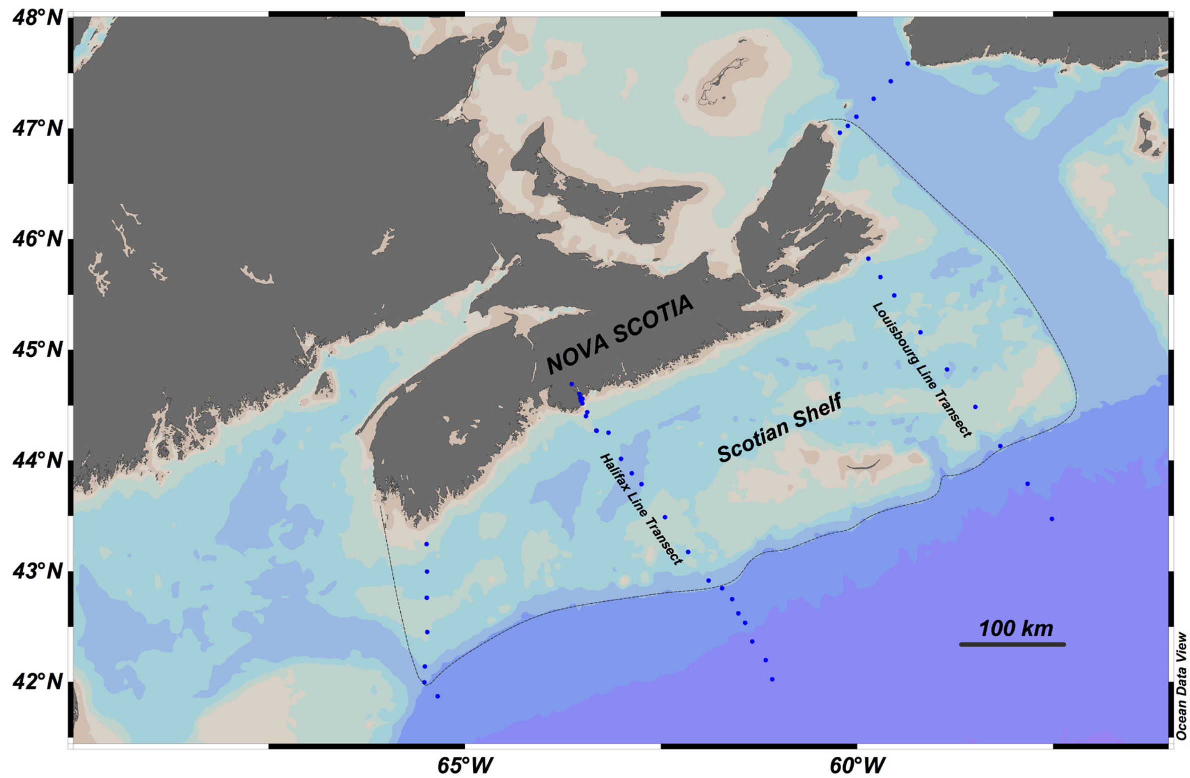
The CO_2 story:

About half of the CO_2 we pump into the atmosphere every year makes its way into the surface ocean. When CO_2 combines with water, it turns into carbonic acid, leading to ocean acidification. This term is essentially self-explanatory: the world's oceans are becoming slightly more acidic every year, which is a major cause for concern for marine wildlife, especially creatures whose hard, protective skeletons are becoming compromised or weakened by the increasingly acidic waters. Examples of potentially threatened organisms include some species of marine plankton, shellfish and coral reefs. Ocean acidification is not only a critical ecological concern to scientists, but it also has huge global conservation, economic and societal implications.

So how do we go about understanding how increased CO_2 inputs might impact marine ecosystems? A logical first step would be to try to get a clear understanding of the marine CO_2 system itself.

In addition to the atmospheric source of CO_2 into the ocean, continents add dissolved carbon to the oceans via rivers and groundwater, and carbon seeps into the ocean from sediments. We also know that once the carbon enters the ocean, it is transported through the ocean by various currents.

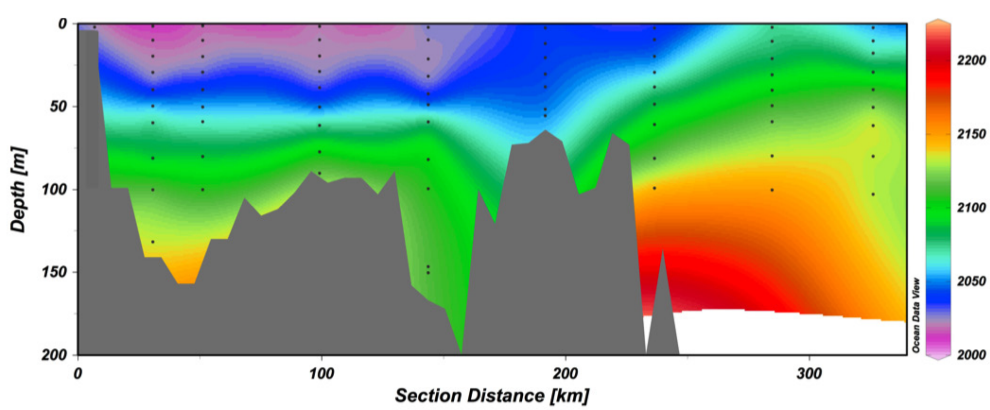
So, if the Atlantic Ocean is one big compartment, can we accurately calculate all of the CO_2 that enters and exits the compartment over a given time? Well, hundreds of kilometres from the shoreline (roughly in the middle of the compartment), the open ocean is on average about 4 km deep, and very little sediment is deposited at those depths. This essentially eliminates both the continental and seabed sources of carbon. For the atmospheric input, recent technological advances, like satellites,



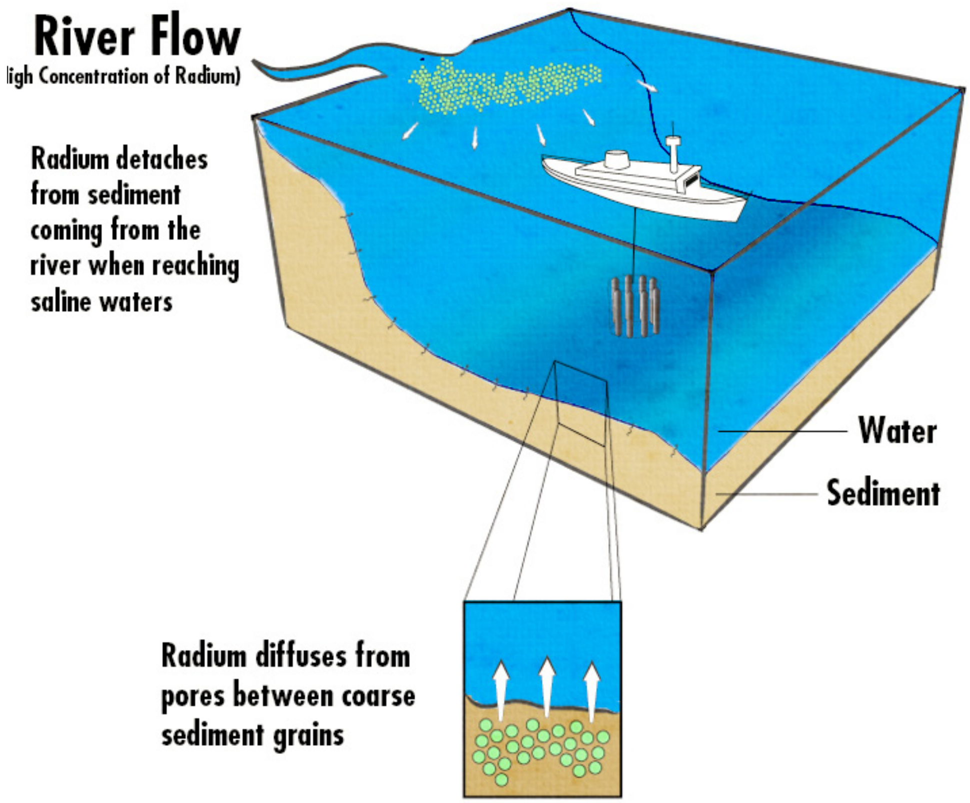
Map of the stations (blue dots) we sample on a typical cruise. The outline of the Scotian Shelf is shown (black dashed line).

have allowed for remarkably accurate estimations for huge expanses of the ocean surface. Using this information in climate models, scientists can now predict both present and future carbon levels in the open ocean. However, once we move closer to the sides of the compartment (the coasts), we encounter shallower waters, rivers, increased biological activity, and complex coastal currents, which all add to the complexity, meaning the accuracies of these large-scale models become compromised.

This is where all of our fieldwork at sea comes in. While previous members of the lab group have focused on the atmospheric source of CO_2, my research involves investigating the sources from continents and the seafloor. To locate and track dissolved substances, like carbon, in the ocean, oceanographers often use chemical tracers. Tracers can be artificial, like adding dye and visually tracking its movement, or they can be naturally occurring, like radium isotopes. In this case, we choose to collect radium isotopes, mostly because they enter the ocean from the two locations that we are interested in (the coasts and the sediments). Radium is also particularly useful because it radioactively decays with time. By collecting



Our "CO_2 map" showing concentrations of dissolved carbon along a series of stations heading offshore along the Louisbourg Line Transect (see map). Note that concentrations tend to increase with depth (see Outgassing section for details). Each black dot represents where we took a sample.



carbon and radium together, we can help unravel the complexities of the coastal carbon system.

Radioisotopes: The internal stopwatch

As scientists, we are all trying to advance knowledge by building upon the work of other scientists. Over 100 years ago, the famous scientist, Ernest Rutherford, discovered the principle of radioactive decay and introduced the concept of "half-lives". Later work established that the half-life of a given radium isotope is exactly 3.66 days. But what does this mean? It is the length of time taken for the radium concentration to decrease by one-half, in other words, if you knew the concentration of radium in a bucket of seawater right now, you would also know that its concentration in that bucket is going to be exactly half in 3.66 days. This principle, what I like to call the "built-in stopwatch", is why radium is such a useful dissolved component of seawater, and a commonly used tracer.

Radium is just one of the numerous radioactive tracers present in the world's oceans. These substances, called radioisotopes, are like tools in a toolbox, each tool having a different half-life, which means it can be used to understand processes that occur on a wide variety of time scales. Radium alone has four different radioisotopes, some that decay away in days, and others that take up to 5000 years. These longer-lived isotopes can be useful for understanding global circulation patterns, while our 3.66-day half-life isotope is useful for faster processes like monitoring tides, or in our case, coastal and seafloor carbon inputs. Radium is particularly useful because we know where it comes from (the land or the sediment) and how it behaves in seawater. Specifically, we know that unlike carbon, its concentration is not affected by any biological processes. Thus it only decreases its concentration at a particular location because of decay and from being transported out of that location.

In a similar way, radioactive decay of carbon isotopes is used to 'carbon date' certain objects, like a piece of an old skeleton, wood or rock. In oceanographic research, we take a number of water samples along a straight line of locations, or transect (for example, see map), away from a source (the coast). Along this transect, we hope to observe changes in radium concentration with distance away from the source. With our knowledge of the half-life, we can use the change in radium concentrations to calculate how fast the water is being transported.
The reason we can't do this with other substances, like carbon, is that to calculate a water 'transport' rate, you need a unit of time, which is provided by the 'internal stopwatch' of radium. The water transports radium and carbon in the same way, because both substances are dissolved in seawater, therefore water transport is also equivalent to carbon transport. So our radium measurements along this transect now relate to carbon transport. Assume then, we can construct a whole map of Radium measurements in the coastal waters and measurements from the surface all the way to the seabed - another source of radium and carbon. With this information, along with our map of CO_2 measurements, it may be possible to calculate transport rates of carbon in multiple places and in multiple directions. One way we use carbon transports on the Scotian Shelf is to help understand a local process called CO_2 outgassing.

An outgassing mechanism?

When the concentration of CO_2 in the atmosphere is higher than that of the surface ocean, the excess CO_2 dissolves into the water, and thus, we have ocean acidification. However, this reaction can happen in both directions, meaning that if CO_2 in the surface ocean becomes higher than the atmospheric level, CO_2 will actually outgas into the atmosphere. On the Scotian Shelf, CO_2 outgassing is a common occurrence, especially in the winter months. This tells us that the surface waters on our local shelf are enriched in CO_2, but it does not give any indication as to where this excess CO_2 is coming from.

As you go deeper into the ocean, the waters become more enriched in CO_2. This is because organic material formed in the sunlit surface waters is broken down by bacteria as is sinks into deeper waters. This breakdown (called respiration) creates CO_2. Using our Scotian Shelf radium measurements to make estimates of transport rates, and our carbon measurements to measure CO_2 gradients, we have found that at slightly deeper depths (about 80 m down), there is a transport of CO_2 enriched waters towards the shoreline. During the winter, strong storm winds blowing over the ocean surface can cause these CO_2 enriched deep waters to be mixed up into the surface, thus providing a previously unknown mechanism for CO_2 outgassing on the Scotian Shelf. With this mechanism in mind, the next step will be to properly measure the extent of this deep water mixing, to see exactly how much it contributes to winter outgassing. We've got a hypothesis, and next April we'll head back out with our radium and carbon sample bottles and see what we can find.

What's next?

The task of understanding the effects of ocean acidification can be daunting because the coastal carbon system is so remarkably complex. Biological carbon uptake (i.e. photosynthesis) occurs in the sunlit surface water, while other marine organisms release CO_2 when they breathe. Carbon can be dissolved, it can be present in larger particles, and can also make up the tissues of marine organisms. Nevertheless, with information about coastal and sediment carbon inputs, we come a few steps closer to understanding this system.

Our mission at sea is simple: collect and analyze as much seawater as we possibly can, from as many places as we can. The work is exhausting, especially when you are trying to keep your balance in a moving laboratory. That being said, oceanographic cruises are a great adventure and working with a team of scientists with the common goal of gaining understanding of this staggeringly complicated system called the ocean, is both a huge challenge and a lot of fun.

THIS RESEARCH WAS SUPPORTED BY A NATURAL SCIENCES AND ENGINEERING RESEARCH COUNCIL OF CANADA (NSERC) GRANT AND THE KILLAM TRUSTS.

William Burt

Will Burt grew up in Vancouver, BC, and became passionate about ocean sciences after assisting a science crew during a 2005 Arctic Ocean expedition. After focusing on chemical oceanography, he revisited the Arctic in 2008 and became enthusiastic about the growing concerns surrounding ocean acidification. After his BSc at the University of Victoria, he switched over to the East coast to begin an MSc at Dalhousie. With a keen interest in conducting fieldwork at sea, working in the CO_2 group with Dr. Helmuth Thomas was an obvious choice. During his PhD research, Will has collected and analyzed radium and carbon together on six multi-week research expeditions, culminating in a three-week intensive survey in the European North Sea. After transferring to the PhD program, he has published two research articles and recently received a Killam Fellowship. Outside of school, Will spends every possible moment playing innumerable sports, hiking, biking, and in general, enjoying life outdoors.

Current Tides

Current Tides Magazine, Dalhousie University
Department of Oceanography, Halifax, B3H 4R2

Sponsored By