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Carbon Chronicles: Understanding the Oceanic Impact of Fossil Fuels

An Interview with Professor James Bishop

BY: ALMA RAZAVILAR, MILLA HECKLER & ANDREW DELANEY

Dr. James Bishop is a distinguished professor of Marine Science, renowned for his expertise in the ocean carbon cycle and its impact on climate change. He earned his B.Sc. in Physical and Inorganic Chemistry from the University of British Columbia and a Sc.D. in Marine Chemistry from the MIT/Woods Hole Oceanographic Institution Joint Program. He currently serves as a Faculty Senior Scientist at Lawrence Berkeley National Laboratory and as a professor in the Department of Earth and Planetary Science at Berkeley.

Dr. Bishop's research focuses on understanding the dynamics of ocean carbon flows and their response to human-induced warming and acidification. He leads pioneering efforts in developing autonomous ocean carbon observing sensors and robots, including the innovative "Ocean Carbon Observer," designed to track carbon concentrations and fluxes in the remote ocean to 1000 meter depths daily for seasons to years. In addition to his work at sea, Dr. Bishop applies ocean robotic technology to study terrestrial ecosystems' water chemistry, emphasizing the interconnection between land and ocean biogeochemical processes.

Recognized for his groundbreaking contributions to marine science, Dr. Bishop continues to inspire progress in understanding and mitigating the impacts of climate change on our oceans.

BSJ: Marine ecosystems are vast and complex. Was there a specific aspect or mystery of the ocean that initially captivated you and led you down the path of exploration and study?

JB: As an undergraduate, I intended to study engineering. Then, in my first year, I aced a chemistry exam. The professor who taught the course, Professor Richard Spratley, offered me a summer opportunity in his lab where he took small molecules, froze them into crystals of solid argon, and then conducted infrared spectroscopy. This experience got me excited about what molecules were and quantum mechanics. There's an interesting connection to Berkeley which I'll return to later.

During this time, I learned many practical skills that I went on to use in other applications. Then in my fourth year, I took a course in oceanography that was really fun. So, I applied to both chemistry and oceanography graduate schools. Simultaneously, our understanding of plate tectonics was rapidly evolving. Every issue of National Geographic magazine would release a new map of the Earth's tectonic plates from scientific analysis of the seafloor. This completely overturned our understanding of the earth. Then, I worked as a biological field assistant for the Canadian Department of Fisheries for two summers. Being surrounded by killer whales and seeing water gushing down the fjords; that is how I got hooked. So, I naturally became more and more interested in marine science and oceanography.

BSJ: How did this interest evolve into your current research on the Biological Carbon Pump?

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JB: Well, when I became a graduate student, everyone knew from profiles of nutrients, such as nitrate and phosphate, that the biological processes of photosynthesis, feeding, sinking of particles, and their remineralization had a strong role in ocean chemistry, but it was very exhausting work to go further. People tried sampling particles directly, and would filter ten-liter volumes of water and would maybe extract 100 micrograms of particulate material that they would analyze. At the time my thesis adviser, John Edmond, said maybe we should just go and collect particles by designing something to get lowered into the ocean and filter large volumes of seawater. This is what I did my Sc.D. dissertation on. I used a ship's electricity to spin a pump and cause water to go through filters and then be discharged through a flow meter. By doing this, we could bring back the material filtered from 20,000 liters of water. Then, we are just left with the easy problem of analyzing the chemistry of the hundreds of milligrams of particles captured from this huge volume of water. We measured particulate organic carbon (POC), nitrogen (PN), inorganic carbon (PIC), biogenic silica (PSi), and a host of other elements. So, ever since I was a graduate student, I have been looking at what is called the "biological carbon pump." Professor Edmond, several years later, was one of the first to dive using the submersible Alvin, to the Galapagos Rift where they collected the first samples of hydrothermal vent fluid. This would end up being incredibly important to our understanding of some of the ocean's chemistry. My life as a graduate student was a life of excitement and new discoveries.

BSJ: Could you break down what the carbon cycle does and the role of particulate inorganic carbon (PIC) in this carbon cycle?

JB: If you look at a diagram of the carbon cycle (Figure 1), you may notice there are no numbers associated with the arrows because they are quite uncertain.

Marine photosynthesizers are small organisms, which are on the order of 1 to 50 microns in size. These are in turn consumed by zooplankton, and even some fish that feed by filtering the water. There is a rain of detritus (another word for particles) and other dinner leavings into the subsurface waters. Some organisms dwelling in deeper waters feed on this sinking material while the material is consumed from within by microbes. The net effect of this process is to cause the pH of surface waters to increase and that encourages the uptake of CO_2 from the atmosphere. This system is called the biological carbon pump.

Some photosynthesizers, called coccolithophores, make plates of calcium carbonate which is the dominant form of PIC. It is a strategy that enhances the rate of carbon dioxide supplied to its metabolic centers in photosynthesis. If you make one mole of calcium carbonate, as a byproduct, you generate a mole of CO_2, which you can create from the highly abundant bicarbonate ion. When these organisms are consumed, the sinking detritus is enriched with dense carbonate particles which enhances its sinking speed.

Now, we ask what happens as CO_2 from anthropogenic sources is slowly causing the ocean pH to decrease, in other words acidifying the ocean. The surface waters will no longer be supersaturated with calcium carbonate. If so, calcifying phytoplankton like coccolithophores may become reduced, PIC in detritus is reduced, detritus – sinks slower, and the overall efficiency of the biological carbon pump is reduced. We worry about that.

Beginning around 1995, profiling floats have been increasingly deployed by an international project called ARGO and have revolutionized how we can operate within the ocean by providing a continuous record of ocean temperature and salinity and currents to kilometer depths; there are presently 4000 floats operating globally. ARGO has greatly improved ocean circulation models and climate monitoring.

Our work uses ARGO technology to learn about how ecosystems function on a year-to-year basis or even a day-to-day basis. By expanding our knowledge, we could begin to form the rules necessary for predictive models. From our current understanding, the answer to these questions does not look great. Through observations and a persistent presence in the ocean, we can continue to learn more and improve our models.

The whole notion of our instruments is to look at how particulates are sinking through different depths. If we can learn the rules for how ecosystems work in response to the physical environment, these models can go forward in time and determine how the biological carbon pump in the ocean may change.

BSJ: What did you find to be your biggest obstacle in developing your understanding of the ocean's carbon pump?

JB: For some background, half of photosynthesis occurs on land and half in the ocean. The land photosynthesizers have lifetimes of the order of two decades. I can look out my office window and see the same tree year after year. In the ocean, photosynthesizers live for a day or two before they get eaten. So, when I first created the ship-lowered particle sampling pumps, I would go on a cruise every three months to the same place and do a bang-up job with the chemistry of particles, but I would gain no insight into the efficiency of nature's carbon pump because you come back three months later and everything is different because it is at least twelve generations later. This is like sitting in my McCone office with the shades down and only being permitted to look out of the window once every 240 years – all the trees would be different. This motivated my lab group to develop robots and sensors that collect continuous data independent of ships.

Additionally, as I went on more of these trips, I improved my sample filtering system. I created a parallel system with 12 filtration units operating simultaneously, and it worked great. At the same time, Ron Zaneveld at OSU developed optical sensors called transmissometers which can detect particle levels in water. When deploying these transmissometers with our pumps we discovered a correlation that the log transform of transmittance or beam attenuation coefficient correlates with particulate organic carbon concentrations. Our first profiling floats, dubbed Carbon Explorers were launched in 2001 with these sensors. They captured the first record of the effects of dust-storm iron fertilization in the North Pacific Ocean. In early 2002, they were deployed in the Southern Ocean and yielded the first measures of purposeful iron-stimulated carbon flux and operated for over a year.

BSJ: Your 2022 paper discusses your sensor for PIC. Can you discuss what you were able to discover from this advanced sensor?

JB: When I was doing my graduate dissertation, I wanted to look at the types of particles on my filter, and I used a Geologist's microscope which used polarized light to aid in mineral identification; in simple terms all you see is black unless there are minerals present that interact with polarized light. The mineral that interacts with the polarized light the most is calcium carbonate, one of the most birefringent minerals in existence, and especially in the ocean, it is the foremost dominant birefringent mineral.

Then, when I built the Carbon Explorer, I wanted to create a sensor that used this same principle. I worked with the same people who invented the transmissometer, to attach polarizers to a light source and then a detector on the other end. In theory, the sensor would only see black unless calcium carbonate particles were present.

Then, some 15 years later in 2018, we participated in our first "science" cruise with this device that went from Adak, Alaska, all the way to Tahiti. The sensor, which was profiled surface to 6000 m depths was a success, but it was obviously still an advanced prototype, so our paper discussed the pros and cons of the device. For example, there was hysteresis in the instrument if you raised and lowered it, but we showed how we could mathematically correct this in the post-processing of the data.

BSJ: Considering the interdisciplinary nature of marine science, how has your background in chemistry shaped your approach to marine science, and how have collaborations with faculty from different backgrounds benefited your research?

JB: In oceanography, collaboration is key and I feel this project exemplifies successful collaboration. The pump systems I began developing could reach depths of up to a kilometer. Since then, reliable battery-powered systems have been developed for the full water column depth. Phoebe Lam, who got her Ph.D. from Berkeley in 2005 and is a professor at UC Santa Cruz, collected particle samples for comparison with our sensor data, resulting in our published 2022 paper. We found good agreement between pump pump-sampled PIC

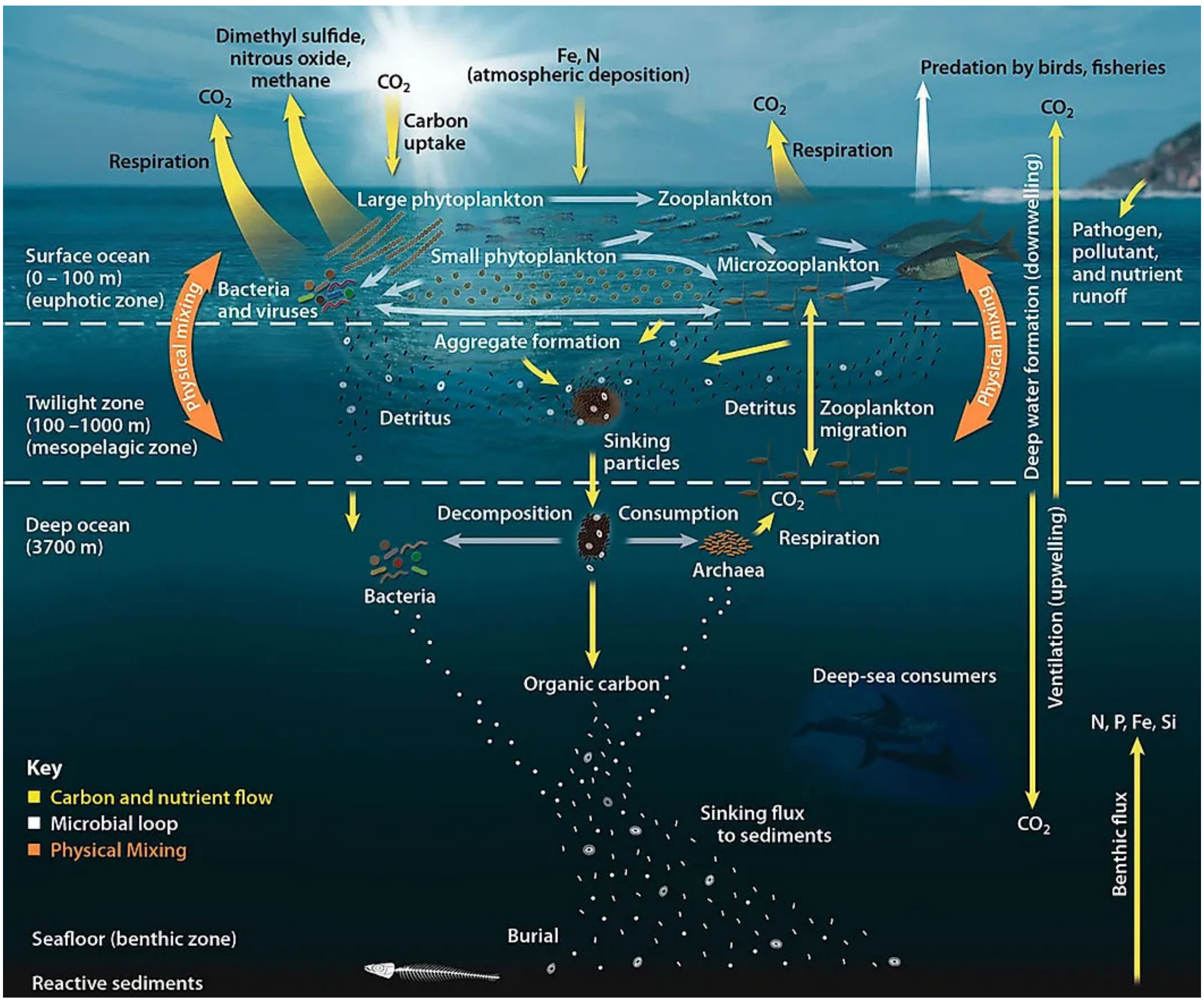

Figure 1: Carbon Flux Cycle: The diagram illustrates the intricate processes involved in the exchange and transformation of carbon within the marine environment, including the various mechanisms such as carbon uptake by phytoplankton through photosynthesis, transfer of carbon through the marine food web, dissolution of atmospheric carbon dioxide (CO2) into seawater, formation of calcium carbonate (CaCO3) by marine organisms

and the PIC sensor. More importantly, we proved the sensor valuable for validating satellite retrieved measurements of PIC which did not always agree with either the pumps or sensors.

Two PIC sensors were again at sea in 2022 on a transect from Tahiti to the Southern Ocean. One is now at the bottom of the ocean near 55°S, 145°W, a casualty of a Christmas-day rogue wave and extreme ship roll which broke the line tethered to 8 battery-powered pumps as well. The 'howling' 50s of the Southern Ocean are not to be ignored as a hazard. Scientists aboard R/V Revelle also "howled" at the loss of equipment, but all were safe. One PIC sensor survived that trip and it has just returned from a study to the coast of Antarctica. We are awaiting data from the 2024 expedition, but I am confident in the robustness of our sensors, transmissometers, and PIC sensors. Pole-to-pole sampling proves this.

BSJ: Your 2021 paper discusses the implementation of four autonomous Carbon Flux Explorers (CFEs). Can you tell us about this advanced sensor?

JB: The Carbon Flux Explorer uses optical imaging to measure the particle flux and its design was created by our team at Lawrence Berkeley Lab. The CFE descends to depth where it begins to drift with the currents there. Stability at depth is ensured, allowing particles to fall into a funnel and accumulate on a flat piece of glass. This glass surface functions like a stage in a microscope. Within the funnel, a light shines down and positioned in the pressure casing looking upwards, there is a five-megapixel camera precisely focused on where the particles accumulate which takes images approximately every half hour. The sample stage is then cleaned using a pump after several image cycles and the process repeats.

We capture images in transmitted light, transmitted cross-polarized light, and also under dark field (side lit) illumination. We use beam attenuation as a way to measure POC flux; cross polarized light yields a proxy for PIC flux, and dark field allows us to classify particles based on their color. These methods offer a unique perspective on particle characteristics.

The CFEs deployed in the 2021 study followed the evolution of carbon fluxes over a month in a filament of upwelled water off the California Coast. We found clear evidence of a rapidly evolving food web. Inshore, most of the sinking carbon flux was due to millimeter-sized Anchovy fecal pellets. Five days later and farther offshore we found that flux was dominated by much smaller fecal pellets. At the end of the experiment and almost 200 km offshore, we found that most flux was carried to depth by millimeter-sized aggregates. Also at all locations, we found evidence that migrating zooplankton and fish were adding to sinking particle flux in the deeper waters. Examples of particles captured in CFE imagery are in Figure 3 below.

BSJ: The continuous operations of these sensors collect a lot of data. What has been your lab's strategy for navigating through this abundance of data?

JB: You are correct in that the challenge arises in managing the vast amount of data generated by this instrument, which totals about two gigabytes per day. Transmitting such a massive volume of data via satellite would take about 23 days which is impractical and because of this, we've been limited to short-term (several day-long) ship-based deployments and recoveries.
In response, I initiated a data project last year, aiming to streamline data processing onboard. The objective was to develop compiled

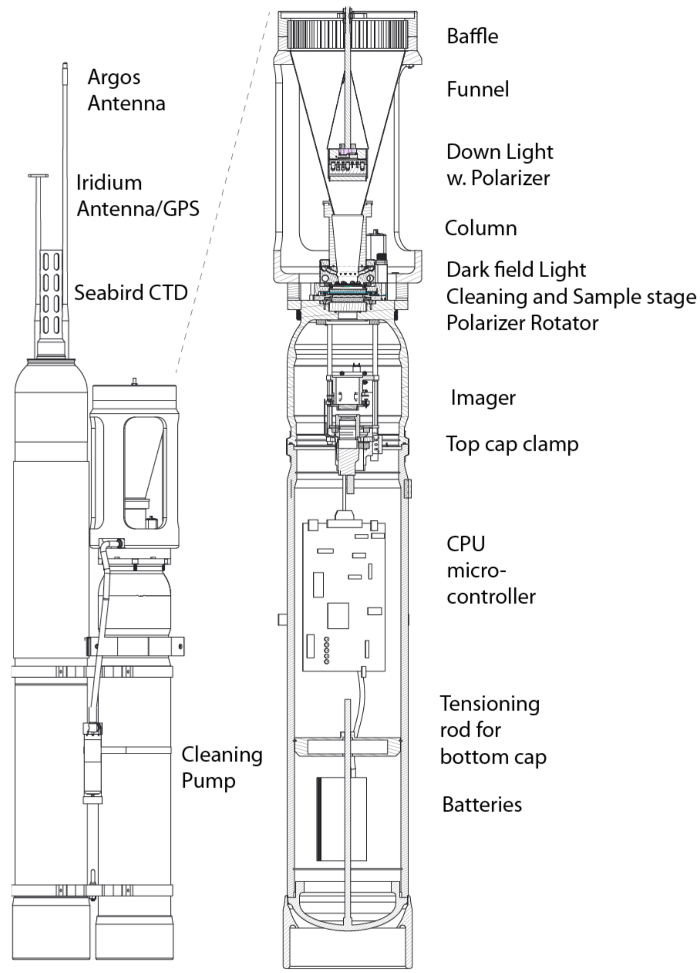

Figure 2: Carbon Flux Explorer: This diagram models the Carbon Flux Explorer built by the Lawrence Berkeley National Laboratory. The data throughout Bishop's studies were collected by the high-resolution camera and sampling system illustrated within the model.

code capable of running on a Raspberry Pi onboard the float. In November 2023, we successfully tested this new approach at sea. Remarkably, the Raspberry Pi executed all the necessary processing tasks in just five minutes—a task that previously took months or even years. Furthermore, the data could be transmitted in real-time. This achievement resulted in an astonishing compression ratio of 200,000-to-1, without compromising data quality. Now the CFE can be deployed for year-long missions. Figure 3 illustrates the results of our computer classification scheme.

BSJ: What insights does studying carbon flux provide?

JB: So, to clarify, the Carbon Flux Explorer and the PIC and transmissometer sensors work in conjunction. At the recent Ocean Sciences Meeting, I described the Ocean Carbon Observer, which can measure POC and PIC concentrations and fluxes. The context for this presentation is that there are currently 4,000 floats deployed globally in a large-scale program called ARGO. These floats, which surface every 10 days to transmit data, provide invaluable insights into deep ocean currents, aiding physical oceanographers in refining their circulation models. Berkeley's OCO can join this array

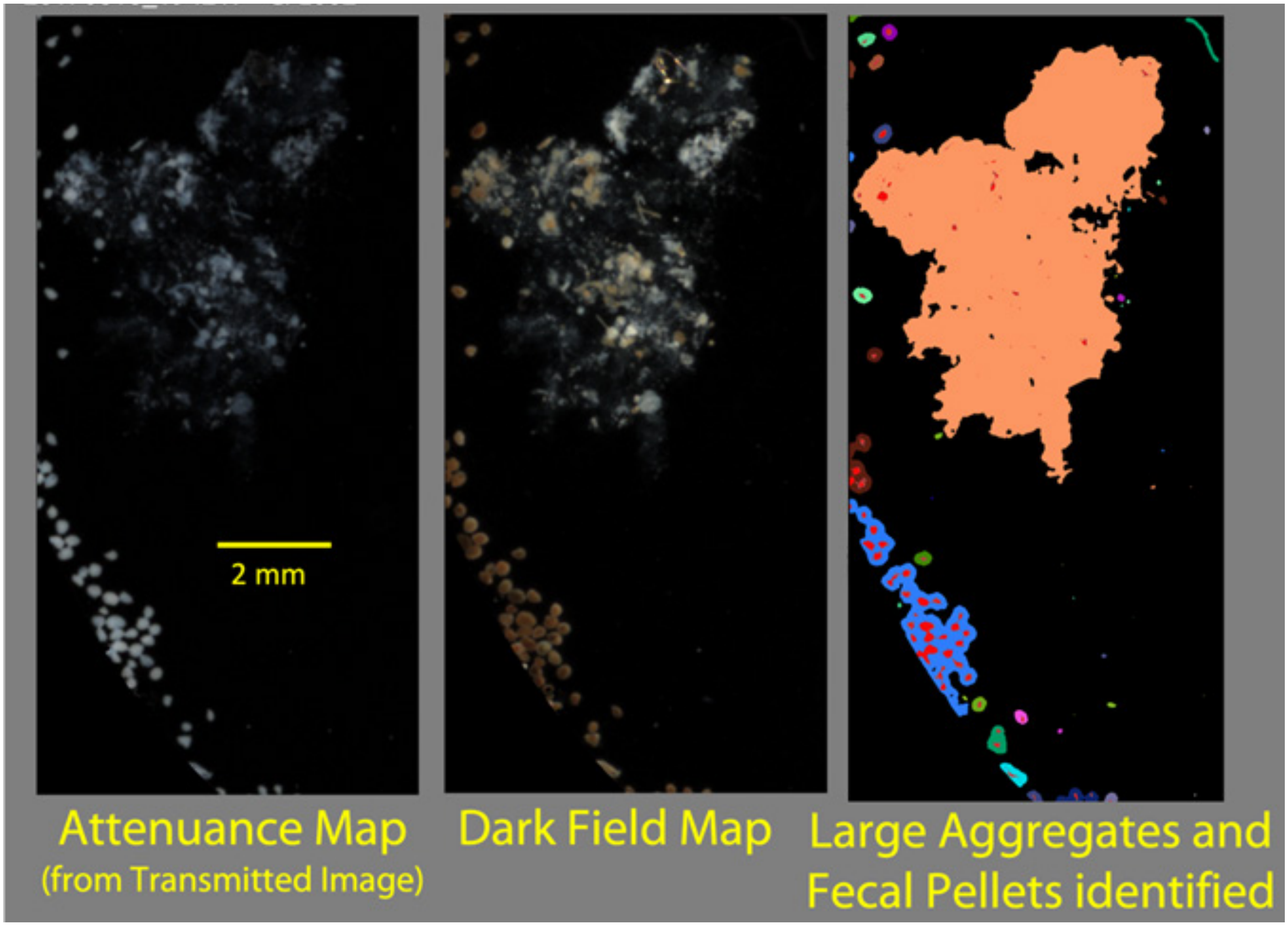

Figure #3: Carbon Flux Explorer Imagery: Images of fecal pellets and large aggregates captured and classified in CFE imagery (Bourne et al. 2021). At left is the attenuance map (derived from transmitted light imagery), center is a dark field image. At right is the computer-generated classification of particles as fecal pellets and aggregates, key to understanding the vector of sinking flux into the deep ocean. The CFE imager can resolve particles at 13 μm resolution.

of floats.

By observing how storm events affect processes in the upper sunlit photic zone and monitoring changes in particle growth rates through particle concentration sensors, we can better understand the flux of carbon into the deep sea. Currently, our understanding of the biological carbon pump is limited to generic diagrams, lacking detailed insights into ecosystem dynamics.

In essence, our approach involves analyzing the remnants of the food web at various depths to discern the organisms present and their activities. This allows us to infer their dietary habits and ecological interactions. In a way, it is like examining neighborhood garbage cans to determine residents' eating habits and where they shop for groceries. This methodology represents a significant breakthrough in our understanding of oceanic processes and ecosystem dynamics. The significance of carbon flux lies in its impact on various ecological processes. For example, the biological carbon pump, which involves the uptake of carbon dioxide by marine organisms through photosynthesis and its subsequent transfer to deeper ocean layers via sinking organic particles, helps mitigate climate change by sequestering carbon in the deep sea. Understanding carbon flux is essential for assessing the health and resilience of marine ecosystems, as well as predicting their response to environmental changes such as ocean acidification and warming.

Therefore, studying carbon flux provides valuable insights into ecosystem dynamics, carbon cycling, and the Earth's climate system, ultimately informing conservation and management efforts aimed at preserving marine biodiversity and ecosystem services.

For marine ecosystems, the only place organisms get their food is through primary production sources. The only place that organisms that dwell deeper in the water column get their food is the particles coming from above carrying organic matter, which provides the energy for their metabolism. So, if you are an organism on the seafloor, you are waiting for things to arrive. So number one, that's a fundamental factor.

The other important thing for people to have is a predictive capability. We know that ocean photosynthesizers account for half of the global primary production, and on average 20% of that primary production is exported from the sunlit surface waters through a depth of 100 meters to deeper waters, carried largely by sinking particles. So it would be nice to know how ecosystems evolve in time and how this flux varies.

BSJ: What was your motivation for having a continuous presence in the ocean?

JB: How do we know the ocean is warming from the anthropogenic CO_2 and other greenhous gases in the atmosphere? Because there are 4,000 ARGO floats all over the world, measuring temperature to a millidegree in accuracy. They can integrate the temperature to see the temperature trends over time, and they can account for the warming of the ocean. The oceans actually take up about 93% of all the heat that is attributable to greenhouse gases.

Many people run ocean circulation models with an added biological carbon cycle, but most of these models assume that ocean biology, including the processing of carbon and its vertical transport rates, is static or unchanging. Why are they doing this: they only have a generic view of how the system works. We can run floats for a year, generating and capturing data in response to storm events that we can track through remote sensing. Then, we can connect the physical forcing of the surface layer due to winds, solar irradiance, vertical mixing, salinity, particle growth rates, and delivery of particles into the deep sea. This will drastically improve the next generation of these models.

BSJ: The vastness of the ocean renders it inaccessible to many, creating a disconnect between people and the vital ecosystems within the ocean. If there is something you could say to the public to convey a sense of urgency to preserve and improve marine ecosystems and environments, what would it be?

JB: On the immediate time scale… keep plastic out of the ocean. It does not need to be there. Several groups are attempting to design means for recovering plastic from the ocean. I applaud these efforts; but, why not simply stop putting plastic in the ocean in the first place? As plastic gets into the ocean, surface currents move it offshore where it eventually accumulates in the center of convergent ocean gyres, so the plastic, which floats, accumulates in remote "garbage patches".

Perhaps most important, education "in person" is key to helping the public be more aware of the ocean. It is mostly out of view and people often think the ocean is a pristine environment. After my graduate degree, when I was a scientist at Columbia University's Lamont Doherty Earth Observatory, they did an experiment where they put out moorings with particle collection devices to try to look at the vertical transfer of carbon over time. The scientists found that within months of them being deployed on the continental shelf, they were no longer there. Why? Fishermen had come along and sank the flotation buoys that kept these devices in the vertical position. The statistic is that every continental shelf in the world is trawled (a process of dragging nets across the seafloor to collect bottom dwellers) at least twice a year. Scientists and fishermen learned to resolve this conflict by listening to each other.

I have taught an EPS82 "Oceans" in the College of Chemistry's, Pimentel 1 auditorium. I recommend that every UC Berkeley student should take a course on the oceans as part of the fundamental curriculum in addition to math, physics, and chemistry. It is fun to learn about the amazing but quite alien water planet that we all depend on.

Looping back to my undergraduate days, it turns out that Pimentel 1 is named after George C Pimentel, who was my advisor to my undergraduate mentor. Who would have predicted that I'd be teaching about oceans in this lecture theater decades later. The rotating stage in Pimentel is built in a repurposed World War 2, battleship gun turret bearing. I was standing on naval history.

Additionally, getting the opportunity to conduct field research is incredible. Occasionally, students come to me interested in doing research, and I have taken about sixty undergraduates out on research cruises that were funded by the National Science Foundation. There's nothing like that experience. The ship leaves the dock, and all you know is that you have a science project out there and you have to overcome any difficulty with resources at hand. The view of the night sky away from cities is worth it all.

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