

CONTENTS

Preface ix

1	I Never Knew the Ocean	1
2	Gravity	15
3	Pressure	45
4	Light	71
5	Motion	99
6	Food	130
7	Family	161
8	Community	188
	Epilogue	206

Further Reading 211

Index 217

CHAPTER 1

I Never Knew the Ocean

Most of us walk unseeing through the world, unaware alike of its beauties, its wonders, and the strange and sometimes terrible intensity of the lives that are being lived about us.

—Rachel Carson, *Silent Spring*

I thought I knew the ocean. At first, the ocean was an escape from the mills and pollution of 1970s Pittsburgh. Not that Pittsburgh was all bad. We had dinosaur bones in the museum, paddlewheel ships in the rivers, and red, inclined trams on the hills. I even enjoyed the “fires of hell” view of the blast furnaces of the Jones & Laughlin steel works that we’d pass on evening drives home from the mall. But the air had a brown edge, the older buildings were black from pollution, and although we did have parks, the trees in them often seemed to be fighting for their lives, pushing their roots through cracked concrete and gravel. My brother and I made the best of it, digging coal mines in our backyard and going on Cub Scout field trips, not to campgrounds but to factories. I loved and still love my hometown, but the unborn biologist in me lived for

late summer when I could escape to a natural world that was happily alive.

Like millions before and after us, for two weeks each August, my family would go to Kill Devil Hills on North Carolina's Outer Banks. After a panicked early morning of my dad saying we couldn't possibly put another item in the trunk of the Dodge, we'd drive through the truck stops of Breezewood, Pennsylvania, around the DC beltline, past the cigarette-shaped headquarters of R. J. Reynolds Tobacco, finally stopping to get peanuts and a fried chicken dinner at the Virginia Diner in Wakefield and to sleep in a motel that—if the fates smiled on us—had a water slide. The next morning we'd shoot past the North Carolina farm towns of Coinjock, Jarvisburg, and Point Harbor, tiny places remembered by thousands of kids because they were the last countdown to the Wright Memorial Bridge that took you across the Currituck Sound, delivering you from an artificial world of bricks and sidewalks to one that mattered.

Having little money, we stayed in what I thought must have been the cheapest hotel on the Outer Banks, a “motor court” consisting of about twelve concrete, single-family structures, which would have looked like public toilets if they weren't painted pink, and had screened porches. Squat and lacking air-conditioning, they were cramped and oven-like, but they put me within a few dozen feet of a world that charted the course of my life for the next fifty years.

Many love the beach, but for me—raised by a lapsed Catholic and an atheist—the ocean immediately became the object of my awe and devotion. For those two weeks, I would spend nearly every waking moment in the water, splashing in the surf when in grade school, moving farther out as I grew, and eventually risking myself in larger and larger waves to see if the sea would finally swallow me up. I'd also talk to the ocean and send

heartfelt goodbyes from the dunes when we had to leave. I was a lonely child, and the ocean provided a link to something powerful and beautiful.

And I thought I knew the ocean. It's true that barrier island beaches are simple, being more or less sand, water, and air, with sea oats and ghost crabs in the sand, a few unseen blue crabs and fish in the water, and seabirds in the air. Pulverized snails, clams, and jellyfish were tossed on the beach, along with some wood and the occasional horseshoe crab, but, overall, one of the charms of a North Carolina beach is its simplicity. However, I thought the beach was the ocean; that somehow the whole ocean was the sound of breaking waves, laughing gulls, and greenish murky water that smelled faintly of rotting seafood. I loved it more than I ever loved anything, but I was mistaking the peel for the apple, the bark for the tree, the skin for the person inside.

However limited in concept, my love for the ocean eventually propelled me to graduate school in marine biology. Coming from a nomadic life of teaching kindergartners, programming computers, and renovating houses, I had no training in biology. I also had no real appreciation for it, and chose the University of North Carolina mostly because I thought Chapel Hill was closer to Kill Devil Hills than it turned out to be. I suppose I was following in the footsteps of my mother, who went to the University of Kiel in Germany solely because it was near the beach. I did learn biology, and more importantly learned to love it, from Bill Kier, a kind and patient mentor. After two years, I had learned to scuba dive and was working on the behavior of brittle stars, which can be thought of either as speedy starfish or as five little snakes tied together by their heads. Being years behind everyone else in my graduate program, I developed a high-risk, low-reward project on vision in these animals,

which never worked but did get me back into the water. I was again spending whole days immersed, but now snorkeling and diving on reef systems in the Florida Keys. This created my second false impression of what the ocean was.

For graduate-school me, the ocean was an oversized aquarium, clear and packed with life. The animals were mostly familiar—snails, clams, crabs, shrimp, sponges, and such—and mostly crawling on the bottom. I learned about these animals—who they were, how they were related, and how they made their way through life. And again, though not formally religious, I was in awe of the diversity and complexity of marine life. If the beach was the peel of the ocean, though, I was still only in the rind, the thin strip of shallow coastal waters that skirts the sea. I happily explored this rind for six years, not stopping to think what might be beyond it.

As for so many people, my life then turned on a chance moment, in this case a conversation with Bill at the end of my graduate training. As I mentioned before, my graduate project was best forgotten. So, I needed a new and hopefully better project to continue the next step of my training, as what is called a “postdoc.” Being interested in eyes and optics, I thought about studying human lens cataracts. Bill, always gentle with his words, suggested that just maybe a lot had already been done on this topic (in fact there are many books and hundreds of articles), but that if I was interested in the transparency of lenses, perhaps I’d be interested in the transparency of entire oceanic animals. I still remember exactly where I was standing in his office, with its barred windows looking out on the Geology Department’s rock garden. “There are so many transparent animals?” “Yes,” he answered, “and many of them are clear as glass. The animals out there look nothing like the animals on land or near shore.” In that moment everything in my life

changed, as I became aware of an immense world that had always been right there, waiting for me to notice.

I did know the open ocean existed, of course, perhaps more than many, because I had crossed it. I knew that, as a baby, I had emigrated to America on an ocean liner, in a pillow-padded orange crate nailed to the deck in my parents' cabin. In the back of my mind, I'd always wanted to go back to sea, to be out of sight of land again on a real ship. But I had no idea that the waters beyond sight of land held animals different from those I saw swimming at the edges of coral reefs. I expected whales, sharks, and fish, with maybe the occasional jellyfish floating by. Over the next ten minutes or so, though, Bill pulled down books from his own time as a postdoc at Woods Hole Oceanographic Institution, showing me pictures of animals that I didn't even know existed, or even could exist.

I had to go. I applied to get a postdoc at Woods Hole or Harbor Branch Oceanographic Institution in Florida, assuming that at least one would appreciate my enthusiasm and overlook my lack of knowledge. Both turned me down flat. I cleaned aquaria for the next year in the teaching labs at UNC and applied again. This time, they both accepted me, each allowing me to do two eighteen-month fellowships one after the other, giving me three years at places where ships and submarines explored the open sea.

I chose to go to Harbor Branch first, arriving in a crammed rented truck, followed by my wife in our hatchback with the stereo, dog, and cats, and started working with Edie Widder, who was so passionate about the various ways that animals emit light that she would answer the phone saying, "bioluminescence." After a quick tour of her lab (painted black floor to ceiling for better optical measurements), followed by gin and tonics at her sound-front home, I asked her when we'd be going out to

sea. She mentioned that the *Edwin Link* would be coming back into port in a few weeks, and we would be sailing on her next. I was immediately impressed that we would be using a ship large enough to have a name, but did my best to act nonchalant.

Harbor Branch Oceanographic was built around an artificial harbor, and my office had enormous windows that overlooked this channel. Each day I worked on my computer, peeking over the monitor now and again to see if the *Edwin Link* was there. One day I heard a deep humming and saw the tip of the bow at the right side of the window. The ship was white, and like the Star Destroyer in the opening moments of *Star Wars*, it kept getting bigger and bigger as more and more of it entered view. And, just like when I was an eleven-year-old boy in the theater in 1977 watching that iconic opening scene, I was more excited than I thought possible. I remember thinking: *This is a ship. Something that is large and strong enough to take us hundreds of miles offshore, for months if needed. It is exploration incarnate.* In truth, the RV *Edwin Link* was only a middling-sized research vessel (about 170 feet long), a converted fishing boat in fact, but at that moment I felt like I was looking at a Saturn V rocket that was preparing to take me to Mars.

A week or so later, after a dirty and sweaty day of loading tubs of nets, cases of deep-sea instruments, tanks of compressed air, and what seemed to be an unnecessary number of boxy old-school monitors, we all hugged our families on the dock and pushed off. After a short passage through the calm, brown Indian River Lagoon, we turned through an inlet straight into the waves of the open sea to begin a four-day trip up the Gulf Stream to Cape Cod, where we would be working for two weeks. It was there that my imagined voyage to the unknown on the *Exploration Incarnate* met the realities of being offshore for the first time.

We had rough weather, meaning high wind. The Gulf Stream, a large river within the ocean, can also be a wavy place. Together, the wind and current built up waves of 12–15 feet, and—aside from my orange-crate trip to the States—I had spent almost no time offshore. It’s an old saying that it’s seasickness when you’re afraid you might die, but bad seasickness when you’re afraid you might not. I was well into the latter stage, and able to keep my food down only by sitting outside at the very middle of the ship (which rocks the least) and locking my eyes on the horizon. Unfortunately, this middle location was exposed, and periodically a large wave would hit me. I soon learned that shoes soaked in salt water are never the same again. My spot also put me in the path of the nauseating diesel fumes from the smokestack. And, because bad things come in threes, I had also gotten unlucky with food; the cook had brought about fifteen drums of “Nutrafat” on board, using it to cook nearly all our meals, which rolled around my plate in a queasy manner. Edie called it my “trial by fire,” and the seasickness, along with other privations and indignities (try showering when you can’t stand), wore me down. But I was there, on the ocean, out of sight of land, exploring it with nets, instruments, and a manned submersible. It was then I learned that I never knew the ocean at all.

The Great Wide Open

The world I saw over the next two weeks was not only unlike the beach and the coral reefs I had played and worked on, it was unlike any habitat I had ever seen or imagined. The water itself was so blue it looked fake. Before graduate school, I had hitchhiked in Oregon and seen Crater Lake. That was the only other time I had seen water like that, looking as though it had been

painted. It was so uniformly and deeply blue that it didn't look like a transparent substance at all, so it shocked me to see a fish and squid far below the surface. I didn't get to scuba dive or go down in the submersible on that first cruise, but when I did a few months later, the blue color below the surface was even more intense, becoming paler as one looked up and deepening to purple as one looked down. The subsurface ocean was also clearer than a swimming pool, and I could easily see large fish, other divers, and even the bottom of our dive boat from over 100 feet away.

Unlike the ocean of all my other experiences, it had no smell and was almost silent unless the wind was high enough to cause whitecaps. In fact, with the ship's engine off, life at sea on calm days is about as quiet as it gets, with only little slaps of water against the hull. Unlike the restless surf of the beach, which I so loved, the ocean below the surface was deathly still.

Above all, the ocean appeared empty. Growing up in Pittsburgh and then living and working in large cities and bustling university towns, my eyes, ears, and even body were used to the continual crush of activity and life. Even the desertlike beaches of North Carolina were full of things to pore over. But offshore, at first glance at least, there was almost nothing. No other ships, no planes, no birds, and—when seen from the deck—often no animals. Just the wake of the ship to let you know you were still going somewhere. This empty feeling was even stronger at night. My former student Julia was on a research cruise a couple years ago and said that those on the night shift would often feel as if there was a black velvet curtain around the ship, one that you could touch if you only reached a bit farther. This curtain appeared to enclose the entire world.

It was the animals, though, the ones that we brought up in the nets and the buckets of the submersible, and that I later saw

directly while underwater, that truly surprised me. Aside from some of the fish and jellyfish, I had never seen anything like them, even though most were related to animals that I had studied in school. There were winged snails that flew through the water like birds, long worms paddling with dozens of crystal oars, and 50-foot-long chains of tubular animals, each pumping to both suck in food and move through the water. Every time we brought in the net or animals from the submersible, I would have to ask, “What on earth is that?” More experienced people would kindly tell me, only for me to often respond, “Are you serious?” In my defense, imagine if someone showed you a gelatinous ball with wings and a sofa-sized snot web that it used for a feeding net—and then told you it was a snail.

After a few cruises at Harbor Branch over the next year, two things became clear. First, that the animals that swim or drift in the water of the ocean, as opposed to living on the bottom, look odd to us because they have to solve the problems of life in a habitat we don't share. They need to stay at a given depth, not get crushed by pressure, move, find food, avoid becoming food, find one another, and make their way through their lives in a habitat with very different rules from those that govern life on land, or even life in coastal waters. They seem alien because the ocean is an alien world to us. The second realization was that this alien world *is* our planet, or at least the vast majority of it. About 90 percent of the earth's habitable space is in the water of the ocean. This is not only because the ocean covers more of the earth's surface than land does, but also because the ocean is much deeper than the range of height that is inhabited on land. The ocean is on average 2 miles deep, while most plants and animals live within a 300-foot-high strip along the surface of the land, with only some birds and insects going several hundred feet above that. We are a water planet, and the rules of the

oceanic realm are the primary rules of life. Our slender terrestrial world, and the rules that govern it, are the exception. To know the ocean is to know our planet.

What This Book Is About

This book is about the adaptations required to thrive in the pelagic portion of the ocean. By “pelagic,” I mean everything that is not the bottom, which includes the surface and the watery world between it and the seafloor. This is also referred to as the “water column,” the “midwater,” or the “open ocean.” While I will occasionally discuss life near the coast, I will mostly focus on the pelagic world that is found far from the shore. It is here that we find adaptations that appear strange to us. By adaptation, I mean the results of evolution via natural selection, where natural selection is the process by which organisms within a species that are better able to live and reproduce become more abundant. This process, which has been termed “climbing mount improbable” by Richard Dawkins, has led in this case to the wondrous forms we see in the pelagic.

This book has two interwoven stories. One is about life in the open sea, particularly in the top 1,000 feet, where there is still a reasonable amount of light (just enough to read this book by). In it, I discuss how pelagic animals, often so strange to us, manage to solve the problems of this world. The first section focuses on the physical issues that these animals face. Chapter 2 discusses the various ways in which the animals keep from sinking to the bottom. Chapters 3 and 4 delve into pressure and light, the first factor going up rapidly with depth, and the second going down even more rapidly. The physics section ends with chapter 5, which explores the various creative ways in which animals move through water and discusses what is known as

“daily vertical migration”—the largest movement of animals on our planet. The rest of the book deals with the biological aspects of this oceanic world. Chapter 6 talks about how animals feed while managing to avoid becoming food themselves. Chapter 7 tries to answer the question of how the residents of the vast and mostly empty sea manage to find one another to reproduce, especially when most are already so camouflaged that they are almost imperceptible. In chapter 8 we end the section with a discussion of communities in the ocean, looking at relationships both within and between species.

Within the story of the animals is the second story of this book, that of the people who study them. Trying to understand a world that is hundreds of miles from land and a thousand feet below you can be frustrating and made worse by the fact that using ships is enormously expensive, typically \$15,000 to \$50,000 per day. Imagine wanting to answer a question and being told that you need to buy a brand new SUV every day for several weeks, and that on some of those days you won't be able to do anything because it's windy or because some piece of machinery is broken and that you still have to pay for the next car. Imagine a hurricane coming, and you being left with nothing but the bill for a couple dozen SUVs.

At sea, plan A never works, and plan B is usually a pipe dream, so you're left with plan C or—more often—plan D, which you built out of old ladders, spackle tubs, and duct tape on the back deck at three a.m. Add in weather, seasickness, and sleeping in a 5 foot 10 bed when you are 6 foot 4, and it all can be a trial. However, there is also camaraderie, seeing things that no one else has seen, and the heart-stopping thrill when something . . . actually . . . works. I like to tell my students that everyone wants to go to sea once, but far fewer ever want to go again. Those few are hooked

for life, though, to be honest, they're crazy. Sarah, a previous postdoc, told me that going to sea was perfect for people who would be happily institutionalized, and Edie once said that offshore life was a week of boredom punctuated by five minutes of rabid excitement. Like the animals, human oceanographers have adapted to an alien environment.

Along with the story of the researchers, this book is also about the technology required to study pelagic habitat. Pressure, gravity, light, and motion are just as important concerns for our equipment as they are for the animals, so specialized techniques are required. Some methods, such as trawling, are quite old, but have been modified so that the animals a mile down can be collected in healthy condition. Others, such as scuba, are more recent, but have also been heavily modified for safe work in the open ocean. There are also the high-tech instruments: the manned submersibles, the unoccupied submersibles (ROVs), and the self-driving AUVs, all built to survive pressures that would crush a car into a cube. The equipment we deploy is often only half the story, because we typically want to work on the animals we collect. We want to understand their senses, how their bodies work, and possibly even their behavior. To do this, we design cramped and chaotic home brew labs, usually brought aboard in multiple plastic tubs and rapidly assembled and tied down right before the ship leaves the dock.

Overall, I want to tell the story of a world that almost no one sees but that nevertheless dominates our planet, and to show how the animals and the researchers manage to survive and thrive within it. I myself will never really know the ocean. Like anything—or anyone—there is always more to learn. On my last cruise we filmed a giant squid using a camera on a mile of rope that we pulled in by hand every night. There's always something new.

What This Book Is Not About

This is not a book about the deep sea. The simple reason for this is that there are already so many excellent books on this subject. The top 1,000 feet of the ocean has received far less attention, despite its being where most of the life is. It's also remarkably beautiful.

This book is also not about the bottom of the sea. This is for a few reasons. First, the animals at the bottom are not nearly as alien as those in the water column. A snail at the bottom at 1,000 feet still looks pretty much like a snail you'd see on a coral reef, but a snail in the water column is unrecognizable. Second, many of the challenges in the ocean—buoyancy, finding one another—are most relevant in the water column.

I am also not writing about algae, bacteria, protists, or viruses. Algae are the primary food source in the oceanic water column, and their consumption and eventual transport to the bottom as fecal pellets are important for removing carbon dioxide from the air. I am not a botanist or microbiologist, though, and am following the rule, “write what you know.” Maybe that's not always the best advice, but I think it's wise for science writing.

Finally, this is not directly a book about conservation. This is not because I don't care about it. Like many biologists, nature is my religion in a visceral way. Nine years ago, I was in Pisa for a conference, during which our family dog Bandit died of cancer back in North Carolina. Distraught, I went into the Pisa Cathedral (next to the leaning tower), and—despite my lack of religious upbringing—lit a candle for my dog and sat down in a pew. Thoughts of my pet developed and grew over the next ten minutes, until eventually I had an internal vision of life on our planet, with pink jellyfish moving just below the surface of the ocean, shiny green tiger beetles crawling through leaf litter,

and fat alligators lying at the edge of Florida swamps, what felt for a moment like all life on earth moving together in an endlessly complex and endlessly evolving dance. This feeling had never been so strong before, but I've felt it my entire life. Our natural world and our ability to appreciate it are stunning gifts, more than we deserve, and never to be cast aside.

We save what we love, and we love what we see. The world below the surface of the open sea has been seen by only a tiny fraction of people. My guess is that only a couple of hundred have gone down in submersibles and perhaps only a few dozen have scuba dived in the open ocean. Before we as scientists can ask people to preserve this important and fragile habitat, we need to show them that it's there and the beauty of what lives in it. To borrow from Doctor Seuss: like Horton the elephant, I need to convey a message from the inhabitants of this hidden world—"We are here."

INDEX

A page number in italics refers to a figure.

- Agalma*, 140
aggressive mimicry, 140
algae: eaten by salps, 111; in marine snow, 143; as primary food in water column, 13. *See also* phytoplankton
ammonia, in cranchiid coelom, 41
amphipods, 115, 159, 199–200
Anableps (four-eyed fish), 87
anaerobic metabolism, in diving mammals, 64
anemones, 109; living on jellyfish, 199, 201
anglerfish, 95, 150
anguilliform locomotion, 102–3
Archimedes' principle, 21
Ascension Island, 183
asexual reproduction, 163
associations between different species, 198–202
Atlantis, 17, 46
ATP, in bioluminescence, 93
AUVs (self-driving submersibles), 12
bacteria: bioluminescent, 95; in marine snow, 143
Bahamas, 120
barnacles, 180, 199
basking sharks, 198, 202
beetle, walking on underside of water, 33
behavior of pelagic animals: difficulty of studying, 194–98; between species, 198–202; within species, 202–5
Belize Barrier Reef, 97–98
bends: diving animals and, 62–63; from helium, 57; from nitrogen, 51–53
Benoit-Bird, Kelly, 123
big squeeze, 80
billfish, cooperative hunting by, 202
bioluminescence, 91–98; bacterial, 95; blue light of, 92, 150; as Edie Widder's specialty, 5, 91, 197–98; false lure with LEDs and, 198; finding a mate and, 164, 169–70; functions of, 94–97; glowing when touched, 93, 95–96; glowing without being touched, 95; of octopus *Japatella*, 169–70; of ostracods, 97–98, 205; of plankton, 74–75, 92; predation and, 95, 96–97; in wake of the ship, 91–92
birds: diving, 57, 61–62, 65, 87; heat exchangers in legs of, 57; preying on flying fish, 104; preying on schooling fish, 203

- bluefin tuna, 149–50
- blue light: bioluminescent, 92, 150;
depth in ocean and, 77–79; pelagic
animals' colors and, 149–50
- blue sea dragon (*Glaucus atlanticus*),
32, 147, 147–48
- blue-water diving. *See* scuba diving,
blue-water
- blue water of open ocean, 7–8, 25, 73–74
- bottom-dwelling animals, 13;
spawning to surface, 171, 172
- box jellies, 109, 139–40
- Brandley, Nick, 130–31
- brittle stars, 3, 179
- broadcast spawning, 171–73, 181
- Brooke, Sandra, 131
- bulk modulus, 57–58
- buoyancy, 20–25; Archimedes'
principle and, 21; blue-water diving
and, 20; density of human body
and, 21–23; depth-controlled
drifting and, 122; of eggs and sperm,
40, 171; moving to keep from
sinking and, 42–44; of surface
dwellers, 31. *See also* gas floats,
nonrigid; gas floats, rigid; liquid
floats; neutral buoyancy
- buoyancy control device (BCD), 21,
23–24
- by-the-wind sailor, 30–31, 31, 32
- camera systems, 12, 197–98, 207
- camouflage. *See* predator avoidance
- Cape Cod, 6, 102
- Capricornia Cays, 101
- captain of research vessel, 191–92
- carbon: in fecal pellets, 13; in marine
snow, 143
- carbon monoxide, 30
- Carinaria*, 27
- caustics of sunlight, 73
- Caves, Eleanor, 201
- Cavolinia*, 43, 43
- cephalopods: jet propulsion by, 108;
vertical migration of, 123. *See also*
nautilus; octopuses; squid
- Cestum veneris*, 117
- Challenger Deep, 39
- chief scientist on ship, 191–92, 207, 209
- chitin, of *Janthina's* bubble raft, 32
- chondrophores, 28, 29–31, 31
- cilia, 117–18
- climate change, 132, 193
- Clione limacina*, 144–46, 145
- cnidarians, 109. *See also* anemones;
corals; medusae
- coastal waters: appearances of, 78–79;
manatees in, 32–33
- cochlea, 117–18
- cod end, 92, 93
- coelom, of cranchiids, 40–41
- collective behavior, 204
- coloration of animals: for communica-
tion, 202, 204–5; of fish herding
prey, 202; for hiding, 149–51; of
Humboldt squid, 135, 204
- colors of light in water, 76–79, 149
- comb jellies, 41, 114, 116–18, 117, 157, 206
- commensal associations, 200–201
- communication of animals, 202, 204–5
- communities: biological definition of,
199; on research vessel, 188–92, 208–10
- communities, pelagic: associations of
different species in, 198–202; limits
to scientific knowledge and, 192–94;
reasons for ignorance about, 194–98;
structured by depth, 123
- compass, and magnetic field, 184
- compressibility of a substance, 57–58
- cone cells, 81, 82, 88

- Continuous Plankton Recorder, 121
cooperative hunting, 202, 204
copepods, 114, 115, 123, 199, 201, 203
coral reefs: broadcast spawning and, 172; cleaner shrimp on, 201; differences from open ocean, 5, 7, 13, 24, 93, 132, 149; larval settlement on, 178
corals, 109; spawning by, 171, 172, 173
corneas: of four-eyed fish, 87; human, 85–86, 159
Corolla, 136, 137, 143
cost of transport, 109, 110
countercurrent exchangers, 67–70
countercurrent multiplier, 69
counterillumination, 95, 155–56
crab larva, 177
cranchiids, 40–41
crustaceans, 114–15; associations with other groups, 199; counterillumination, 155–56; diel vertical migration of, 123; larval, 177, 178; transparent, 157, 159. *See also* amphipods; barnacles; copepods; isopods; krill; ostracods; shrimp; shrimp-like animals
ctenophores, 42
cubomedusae. *See* box jellies
currents: deep currents, 119, 121–22; eggs and sperm in surface of, 171–72; filter feeders in, 136–39; global surface pattern of, 118–19
Cystisoma, 159, 173, 199
dark adaptation, 79, 80–81
Dawkins, Richard, 10
decibels, 80
decompression chamber, 57
decompression sickness, 51–53
deep sea, 13
Deepstaria, 110, 201
Denton, Eric, 152, 153
depth-controlled drifting, 121–22
diel vertical migration, 123–29; freshwater, 124, 125; light levels and, 127–29; predation and, 124–27
diffusion of molecules, 165
direct development, 178
dive reflex, 64–65
diving animals, 60–66; birds, 57, 61–62, 65, 87
doliolids, 113, 136
dolphins, 60, 62, 166, 202
drifting animals, 118–22
drifting blue-water divers, 120
drowning: falling overboard and, 16–18; mechanisms of, 22–23
dugongs, 33, 60
ears, popping, 35–36
Edwin Link research vessel, 6, 99, 207
eels: anguilliform locomotion and, 103; countercurrent exchanger of, 67–68, 69; larval, 140–43, 158, 177
eggs of pelagic animals: lipids in, 40. *See also* spawning
electromagnetic waves, 76
electroretinography (ERG), 82–83, 84
elephant seals, 60, 61, 63, 186–87
emperor penguins, 62, 65
evolution, 10, 129. *See also* natural selection
eyes: hidden with mirrors, 154–55. *See also* corneas; lenses; pupils of eyes; retinas; vision of humans; vision of pelagic animals
face masks, 50, 86
falling overboard, 16–18
fat: buoyancy of human body and, 22; buoyancy of sharks and, 40; nitrogen diffusing into, 52, 54. *See also* lipids

- feather duster worms, 136
feather stars, 136
fecal pellets, 13, 111
filter feeders, 136–40; marine snow and, 143
fireflies, 74, 91, 93, 97
fish: associations with other animals, 199, 201; counterilluminating, 155–56; currents and, 120; diel vertical migration of, 123; flying fish, 103–4; larvae of, 178; lenses of, 86–87; with light organs for finding food, 95; lights and color on bodies of, 155–56, 204–5; living at 26,000 feet, 57; locomotion of, 102–3, 105; low-density lipids in, 40; as predators, 104; as prey of bigger fish, 133; salmon reproduction, 181; schooling of, 202–5; silvery, 151–53; social behavior of large species, 202; spawning by, 171; swim bladders of, 34–35, 36, 42, 66–70, 166; transparent, 157; ultrablack species of, 150–51
Fisher, Erin, 92
flotation vest. *See* buoyancy control device (BCD)
flying fish, 103–4
food for pelagic animals: for eel larvae, 140–43; for gymnosomes, 143–46; marine snow as, 142–43; trade-off of specialized diet and, 146. *See also* predation in open ocean
food on research vessels, 130–31
four-eyed fish (*Anableps*), 87
Frank, Tammy, 82, 84, 128, 131
free divers, 53, 62
freshwater systems: adult eels in, 141; vertical migration in, 124, 125
frigate bird, preying on flying fish, 104
Galapagos Islands, marine iguanas of, 105
Gardner, Martin, 170
gas floats, nonrigid: with gastrointestinal gas, 32–33, 42; of siphonophores, 37; swim bladders of fish, 34–35, 36, 42, 66–70, 166. *See also* buoyancy control device (BCD)
gas floats, rigid: of nautilus, 37–39
giant squid, 12, 207, 210
gills, 60
glass eels, 141, 142
glass octopus (*Vitreledonella richardi*), 167–69, 168
Glaucus atlanticus, 32, 147, 147–48
global conveyor belt, 119
glycosaminoglycans, in leptocephali, 142
gossamer worms, 116, 116
gravity: inverse square law of, 18–19; pelagic animals and, 20, 21, 25, 26–28
Great Barrier Reef, 101
green bomber worm, 96
green light: of bioluminescent octopus *Japetella*, 169–70; phytoplankton and, 78; water transparent to, 77, 78
green sea turtles, 183, 184–86
guanine: of fish scales, 153; of swim bladder, 68
Gulf of Mexico, 25, 118, 142, 207
Gulf Stream: causes of, 118–19; flying fish in, 103; sea turtles in, 183, 184; silvery fish in, 151; traveling up, 6–7
gymnosome pteropods, 143–46, 145
Haldane, J. B. S., 114
Harbison, Rich, 195–96
Harbor Branch Oceanographic Institution, 5–6, 9
Hardy, Alister, 121
hectocotylus, 167–69

- helium, for divers from submersible, 56–57
- hemoglobin: carbon monoxide and, 30; carrying oxygen, 52; of diving mammals, 63–64; of emperor penguin, 65; of fish, 69
- Henry's law, 52
- Heron Island, 101
- Herring, Peter, 132
- heteropods, 26, 27, 154. *See also* snails, pelagic
- hiding. *See* predator avoidance
- holoplankton, 178–79
- Humboldt squid, 135, 204
- hunting by pelagic animals, 134–35, 144, 202, 204. *See also* predation in open ocean
- Hurricane Camille, 49
- hydroids, 199
- hydromedusae, 41–42, 109, 139–40
- hyperbaric chambers, 54–55
- Hyperietta*, 200
- hyperiid amphipods, 199–200
- iguanas, marine, 105
- imprinting by young animals, 185–86
- insects, walking on underside of water, 33
- inverse square law, 18–19
- isolume hypothesis, 127–29
- isopods, 199, 201
- Janthina*, 32, 33
- Japanese flying squid (*Todarodes pacificus*), 108
- Japetella*, 169–70
- jellyfish: associations with other animals, 199, 201; drifting in currents, 120; jet propulsion by, 106; sounds and, 167. *See also* medusae
- jet propulsion, 106–14; of cephalopods, 108; of medusae, 109–10; peaceful world of, 114; relatively efficient underwater, 106–7; of salps, 110–13; of siphonophores, 113–14; of squid, 108–9
- Johnson-Sea-Link*: battery of, 196; in diel migration study, 128; experiencing a dive of, 72–75; scuba diving from, 46–47, 56–57
- Katija, Kakani, 139
- Kier, Bill, 3, 4–5, 54, 176, 193
- krill: paddling motion of, 115; vertical migration of, 123–24, 126
- laboratory, shipboard, 12, 15, 16, 83–84
- lactic acid: from anaerobic metabolism, 64; inflation of swim bladder and, 69
- lakes, diel vertical migration in, 124, 125
- larvaceans, 136–39, 138
- larvae, pelagic, 176, 177, 178; drifting in currents, 120; of eels, 140–43, 158, 177; metamorphosis of, 179–80; settlement of, 178, 180–81; sinking rate of, 27–28
- leadership, 191–92
- lenses: of humans, 85–86, 159; of pelagic animals, 86–87, 90; of terrestrial animals, 86
- leptocephali, 140–42, 177; eating marine snow, 142–43; transparency of, 158
- lifeboat test, 190–91, 192
- light: colors in water and, 76–79, 149; diel vertical migration and, 127–29; exponential relation to depth, 77–78; logarithmic sensing of, 79–80; in submersible dive, 72–75; in top 1000 feet, 10; as visible radiation, 76

- light organs, 95, 204–5; for counterillumination, 155–56. *See also* bioluminescence
- light scattering, 158, 159
- Limacina*, 43–44, 144–46
- lipids: providing buoyancy of eggs and sperm, 40, 171. *See also* fat
- liquid floats, 39–42
- lockout diving, 47, 56–57, 59
- locomotion. *See* motion of pelagic animals
- logarithmic sensing, 79–80
- loggerhead sea turtles, Atlantic, 182–86
- Lohmann, Ken and Cathy, 182, 184, 185
- LoLAR (low-light radiometer), 128
- lookdown fish, 153
- Lorenz, Konrad, 185
- loudness, decibel units of, 80
- luciferase, 93
- luciferin, 93
- lungs: buoyancy and, 21, 22–23; cilia moving stuff out of, 118; of diving mammals, 62–63; evolution of, 34; exhaling as one ascends and, 24; oxygen toxicity and, 56; uncontrolled ascent or descent and, 24
- Madin, Larry, 139
- magnetic field and navigation: of elephant seals, 187; of turtles, 184–86
- mammals. *See* marine mammals
- manatees, 32–33, 60
- man-of-war. *See* Portuguese man-of-war (*Physalia physalis*)
- mantis shrimp, 144
- marine mammals: diving to great depths, 57; ocean currents and, 120; oxygen for, 63–64; pregnancy in, 173; social behavior of, 202; swimming motion of, 104–5. *See also* dolphins; dugongs; manatees; whales
- marine snow, 142–43
- marlin, 104, 202
- Marshall, Justin, 101
- Martini's law, 54
- mask squeeze, 50
- mating strategies of pelagic animals, 164–70
- McCoy, Dakota (Cody), 201
- Medusa camera system, 197, 207
- medusae: jet propulsion by, 109–10; mostly water, 157; nematocysts of, 139–40; subgroups of, 109, 139; transparency of, 157, 158–59. *See also* jellyfish
- melanin, 150
- meroplankton, 178–79
- Merz, Rachel, 175–76
- mesocosms, 125, 128
- mesoglea, 158–59
- metamorphosis, 179–80
- methane, in manatee intestines, 33
- migration in groups, 202, 204. *See also* vertical migration
- mimicry, aggressive, 140
- mirrors, used for hiding, 151–55
- monkey fist, 197
- Monterey Bay Aquarium Research Institute, 123, 139
- moon jellies, 25, 110
- moon pool hatch, 72
- moon pool in submersible, 47
- More, Thomas, 185
- motion of pelagic animals: of drifters, 118–22; of jettiers, 106–14; of paddlers, 114–18; of swimmers, 102–5
- motion of research vessel, 100
- mucus, in marine snow, 143
- mucus houses, of larvae, 137–39, 138

- mucus nets, of pseudotoecosomes, 136
- myoglobin, of diving mammals, 63–64, 65
- naked pteropods, 143–46, 145
- nanoplankton, 138
- natal homers, 181; elephant seals, 186–87; salmon, 181; sea turtles, 182–86
- National Oceanic and Atmospheric Administration, 207
- natural selection, 10, 25. *See also* evolution
- nautilus, 37–39, 108
- nectophores, 113–14
- nematocysts: of medusae, 139–40; used by *Glaucaus*, 32, 147–48
- net sampling, 132, 195–96, 199. *See also* trawling
- neutral buoyancy: humans close to, 22; of motionless sand tiger, 42; nonfloating siphonophores and, 37; pelagic animals close to, 26–27, 42; of submersibles, 72
- Newton, Isaac, 194
- nitrogen: as 80 percent of air, 52; the bends and, 52–53; in float of *Velevella velevella*, 31; inflation of swim bladder and, 69; lung pressure of, 24
- nitrogen narcosis, 54–55; diving animals and, 62–63
- ocean: as 90% of earth's habitable space, 9. *See also* coastal waters; open ocean
- octopuses: associations with other groups, 199; bioluminescent, 169–70; intelligence of, 204; mating strategies of, 167–70; moving by jet propulsion, 106, 108; transparent, 157, 167–69, 168
- Olive ridley sea turtle, 183
- open ocean, 10; with alien-seeming animals, 8–10; with average depth of 2 miles, 57; clarity of water in, 8, 24; dearth of surfaces in, 200; deeply blue water of, 7–8, 25, 73–74; immensity of, 99–101; lack of reference points in, 100, 120; nutrient poor, 131–32, 135; top 1000 feet of, 10, 13
- orcas, 135, 166
- Osborn, Karen, 150
- osmosis: cranchiid coelomic fluid and, 41; in firing of nematocyst, 139–40; in nautilus, 38–39
- ostracods: bioluminescent, 97–98, 205; as paddlers, 114–15
- otters, 60
- oxygen: for air-breathing animals, 63–66; for animals without air cavities, 59–60; in bioluminescent mechanism, 93; dangerous at high pressure, 55; decreased in warmer water, 132; dissolved in water, 59; in diving mammals, 63–64; lung pressure of, 24; swim bladders and, 68–69; through gills or skin, 60; water pressure and, 59
- oxygen tension, 59, 68–69
- oxygen toxicity: diving animals and, 62–63; scuba divers and, 55–56
- oysters, spawning of, 172, 173
- paddling animals, 114–18
- pair bonding, 202, 204
- parasitic associations, 200–202
- pelagic world. *See* open ocean
- Pelican* research vessel, 25
- penguins, diving, 62, 65
- Phaistos Disc, 205
- pheromones, diffusion of, 165

- photon noise, and vision, 89–90
- photosynthesis: optical properties of
water and, 76; by phytoplankton, 78
- Phronima*, 173–74, 174, 199–200
- phytoplankton: more productive in
colder water, 88; photosynthesis by,
78; vertical migrators grazing on,
126–27. *See also* algae
- plankton: bioluminescent, 74–75, 92;
freshwater, 125; nanoplankton, 138.
See also phytoplankton
- plankton mimics, 122
- Plymouth Marine Lab, 152
- pneumatophore, 30
- Point Sur*, 207
- Portuguese man-of-war (*Physalia physalis*), 29, 29, 30, 31–32, 113; *Glaucus*
borrowing weapons of, 32, 148
- predation in open ocean: biolumines-
cence used in, 95; compared to other
habitats, 132–34; eggs and sperm as
prey in, 171–72; by filter feeders,
136–40; by hunters, 104, 134–35,
144–46, 202, 204; by whales, 60,
135, 166
- predator avoidance, 146–60; with
bioluminescence, 96–97; with
counterillumination, 155–56; diel
vertical migration and, 124–27; with
mirrors, 151–55; schooling and, 203;
by shrimp, 115; with skin coloration,
149–51; with toxins, venoms, or foul
tastes, 146–49; with transparency,
156–60
- preformationism, 176
- pressure. *See* water pressure
- Pristigenys*, 102
- pseudothecosome pteropods, 26–27,
43, 143; *Corolla*, 136, 137, 143; mucus
net of, 136
- pteropods: carried by *Hyperietta*, 200;
gymnosome (naked), 143–46, 145;
hydroids living on shells of, 199;
locomotion of, 115–16; low-density
lipids in, 40; pseudothecosome,
26–27, 43, 136, 137, 143; thecosome, 43,
43–44, 143, 144–46; three groups of,
143; toxic, 200. *See also* snails, pelagic
pupils of eyes, 80, 87, 88, 90
- rapture of the deep, 55
- Raymond, Erika, 197
- rays, locomotion of, 104–5
- Read, Andy, 61
- red pigments, 150
- regulator of scuba gear, 23, 51
- remoras, 199, 201
- reptiles, marine, 104–5
- research vessels: *Atlantis*, 17, 46; captain
of, 191–92; changes in humans on,
206–7; chief scientist on, 191–92, 207,
209; communication from, 161–63;
community on, 188–92, 208–10;
difficulties of research on, 84–85;
distant from medical help, 100;
Edwin Link, 6, 99, 207; flying fish
landing on, 104; food on, 130–31;
fuel consumption by, 100; laborato-
ries on, 12, 15, 16, 83–84; lifeboat test
on, 190–91, 192; living areas of, 15;
love for, 207–8; machinery of, 15–16;
Pelican, 25; *Point Sur*, 207; without
sense of forward motion, 100
- rete mirabile, in swim bladder, 67–70
- retinas: electroretinography and, 82–83,
84; with larger size, 90; oxygen
toxicity and, 56; with tapetum, 88
- rod cells, 81, 82, 88, 89
- Roethke, Theodore, 193
- Root effect, in swim bladder, 69

- ROVs (remotely operated vehicles), 12;
advantages of, 199; animals disturbed
by, 196; captain's approval for deploy-
ment of, 192; controlled by van, 210;
in Gulf of Mexico, 207; launching,
208–9; sinkers seen from, 139
- safety briefing, 16
- safety sausages, 101
- sailfish, 104, 202
- salmon, 181
- salp bloom, 111
- salps: in associations with other
animals, 199–200; chains of, 111, 112,
113; diel vertical migration of,
123–24, 126; as filter feeders, 136; jet
propulsion by, 110–13; *Phronima*
parasitic on, 173–74, 174, 199–200
- sand tiger shark, 42
- Sargasso Sea: clear and empty, 78;
loggerhead sea turtles in, 183, 184–85
- schooling of animals, 202–4
- scuba diving, blue-water: breathing in,
49–50, 51–52; buoyancy control
device (BCD) in, 21, 23–24; com-
pared to reef diving, 20, 21; done
by few people in open ocean, 14;
drifting with current, 120; first
experience of, 25; float used in,
20, 94; heavily modified for open
ocean, 12; at night, 81–82, 120;
nitrogen narcosis in, 55; peaceful,
25, 114; popping ears and, 36; as
research method, 197, 199; from
submersible at 1000 feet, 47, 56–57,
59; surfacing to absence of dive
boat, 101; tether systems for, 20–21,
24–25; water pressure and, 49–57
- scyphomedusae, 139–40. *See also*
jellyfish
- seals, 60, 62, 63–64; elephant seals, 60,
61, 63, 186–87
- seasickness, 7, 11, 188
- sea slugs, stealing toxins, 32, 147–48, 149
- sea snakes, 105
- sea turtles: locomotion of, 105; natal
homing of, 182–86; ocean currents
and, 120; preying on surface dwell-
ers, 32
- seawater: density compared to fresh-
water, 41; modified as liquid float,
40–42
- Seibel, Brad, 18, 36
- selfish herd theory, 203
- senses of animals, 167
- sexual reproduction, 163–70; benefit
of, 164; of bioluminescent octopus,
169–70; finding a mate for, 164–70;
of glass octopus, 167–69; parasitic
forms of, 173–75, 174; protecting the
young and, 173–75, 174; of spawners,
170–73. *See also* larvae, pelagic
- Shackleton, Ernest, 191
- sharks: basking sharks, 198, 202;
buoyancy of, 40, 42; fat in livers of,
40; locomotion of, 105; negatively
buoyant species of, 103; ocean
currents and, 120; remoras and, 199,
201; scuba divers encountering, 133,
198; small fish surrounding, 199, 201
- ships. *See* research vessels
- shrimp: abundant over large areas, 203;
with bioluminescent organs, 95;
cleaner shrimp, 201; counterillumi-
nating, 156; with fish associations on
reef, 201; mantis shrimp, 144; moving
to keep from sinking, 42; as paddlers,
114–15; sounds and, 167; transpar-
ent, 159–60. *See also* crustaceans
- shrimp-like animals, 97, 114–15, 120

- sinkers, of larvaceans, 138–39
- siphonophores, 28–30; crustaceans associated with, 199; gas floats of underwater species, 33–34, 37; jet propulsion by, 113–14; with nematocyst lures, 140. *See also* Portuguese man-of-war (*Physalia physalis*)
- siphuncle, of nautilus, 38
- skates, locomotion of, 104–5
- smell, and finding a mate, 164–65
- Smithsonian's National Museum of Natural History, 150
- snails, pelagic: drifting in currents, 120; locomotion of, 114, 115–16; transparent, 157. *See also* heteropods; pteropods
- snails, surface-dwelling, 32, 33
- Snell's window, 152
- snorkels, 49
- social behavior within species, 202–5
- SOFAR sound channel, 166
- sound: decibel units of, 80; finding a mate and, 165–67
- spatial summation, 88–90
- spawning, 170–73; of men-of-war, 31
- sperm whales: diving to 7000 feet, 60; as predators, 60, 135, 166; sonar used by, 166
- squid: color patterns on, 135, 204; counterilluminating, 155–56; cranchiids, 40–41; giant squid caught on camera, 12, 207, 210; hiding with mirrors, 153–54; as hunters, 135; jet propulsion by, 108–9; light organs of, 95, 204–5; with needle-shaped stomach, 154; ocean currents and, 120; pair bonding in, 202; routine motion with fins, 109; social behavior of, 202; transparent, 157
- starfish: larvae killed by, 181; spawning by, 172
- statocysts, of jellyfish, 167
- stomachs, camouflaged, 154
- stomatopod larva, 177
- submersibles, 12, 14; buoyancy control by, 38; captain's approval of deployment, 192; deep-sea light measurements with, 92–93; disturbing animals, 196, 199; first dive in, 71–75; humor needed in, 190; *Johnson-Sea-Link*, 46–47, 56–57, 72–75, 128, 196; pre-dive meeting and, 71; scuba diving from, 47, 56–57, 59; self-driving (AUVs), 12; structure of, 46–47. *See also* ROVs (remotely operated vehicles)
- sulfate ions, removed for buoyancy, 41
- sunfish (*Mola mola*), 105
- surface dwellers, 28–33
- survival float, 22
- survival suit, 16
- Sutton, Tracey, 16–17, 142
- swim bladders of fish, 34–35, 36, 42, 66–70, 166
- swimming animals, 102–5
- swimming humans, 119
- symbiotic associations, 200–201; of bioluminescent bacteria, 95
- tapetum, 88
- temperature, and depth, 123
- temporal summation, 90–91
- tension of gas in solution, 59, 68–69
- tentacle filter feeders, 139–40
- tether system, 20–21, 24–25
- tecosome pteropods, 43, 43–44, 143, 144–46
- threshold hypothesis, 127–29

- thunniform locomotion, 102–3
- tomopterid worms, 116, 116
- tornaria larva, 177
- Torres, Jose, 142
- toxicity, to avoid predators, 146–49
- transparent animals, 156–60; octopuses, 157, 167–69, 168
- trawling, 12, 16, 92, 207. *See also* net sampling
- Trieste* bathyscaphe, 39–40
- tuna: bluefin hidden by colors, 149–50; cooperative hunting by, 202; flying fish as prey of, 104; thunniform locomotion of, 103
- Tyack, Peter, 61
- ultraviolet radiation: diel vertical migration and, 125; dropping with depth, 123; spawning and, 171, 172; surface-dwelling animals and, 32
- Vantablack, 151
- Velella velella*, 30–31, 31, 32
- vertical migration: catch in towed net and, 132; depth-controlled drifting and, 121–22; diel (daily), 123–29. *See also* migration in groups
- vision of humans: adapted to illumination, 79, 80–81; cornea and lens of, 85–86; worse underwater, 85–86
- vision of pelagic animals, 81–82, 85–91; blueness and, 82; of brittle stars, 3; darkness and, 81–82, 87–91; limited distance of, 164; optical properties of water and, 78; photon noise and, 89–90. *See also* eyes
- volcanic vent communities, 180
- wasps, parasitic, 174–75
- water: compressibility of, 57–58; optical properties of, 76–79; pelagic animals composed mostly of, 166; as primary component of most animals, 59; weight and density of, 48–49
- water column, 10, 13
- water pressure: of 1 atmosphere for 30 feet of depth, 49, 77; air-breathing animals and, 60–66; animals without air cavities and, 57–60; dangers for scuba divers and, 50–57; dissolved oxygen not affected by, 59; scuba diving at 1000 feet and, 47
- waves, force of, 48–49
- whales: crustaceans living on, 199; diving, 53, 60–61, 62; as predators, 60, 135, 166; social behavior of, 202; sound used by, 166; tagging of, 61
- Widder, Edie, 5–6, 7, 12, 16, 85, 162; bioluminescence and, 5, 91–92, 197–98; vertical migration and, 128, 132
- wind: global surface currents and, 118–19; surface-dwelling animals and, 30–31, 32
- winged snails. *See* pteropods
- Wistari Reef, 101
- Wolcott, Tom and Donna, 122
- Woods Hole Oceanographic Institution, 17, 46, 61, 139, 192, 195
- worms, pelagic, 114, 115–16, 116, 120, 157
- Young, Craig, 71
- Zylinski, Sarah, 12, 84