nothing to be done about it except duck. Soon, one hopes, these retrograde responses and the administration they represent will be left behind by public concern and by corporations finally recognizing that bundles of money can be made by doing the obvious sensible thing.

For now the question hangs, how much freshening, how much carbon dioxide can the ocean handle before the feedbacks kick in? The term "tipping point," borrowed from epidemiology and recently popularized by Malcolm Gladwell's book by that title, has entered the vocabulary of global warming, referring to the threshold at which a series of relatively small feedbacks produce a sudden and disproportional impact. Another way to say it is that beyond the tipping point, past responses in the climate systems no longer predict future responses. Then, as scientists put it, things go all "nonlinear." The editors of *Nature* wrote in the June 15, 2006, issue: "Anyone claiming to know for sure when a particular tipping point will be reached should be treated with suspicion—and so must anyone who suggests that no tipping point will ever be reached."

I like the way Wallace Broecker famously put it: "The climate is an angry beast, and we're poking it with sticks."

Chapter 13

HURRICANES AND CTDs

Hoping to talk myself aboard, I phoned Chris Meinen, who was to be chief scientist on the NOAA ship *Ronald H. Brown*, at his Key Biscayne office in the Atlantic Oceanographic and Meteorological Laboratory (AOML), an arm of the National Oceanic and Atmospheric Administration (NOAA), which in turn is a branch of the Federal Department of Commerce, for some reason. The ship is named after Bill Clinton's commerce secretary, who was killed in a plane crash in Bosnia in 1996. I had a spiel all set about how I'd already been out on *Oceanus* with John Toole, and I'd been to sea a fair bit on sailboats, I'm not a danger to myself or others, and I'm trying to learn their science from the deck of—

"Will you work?"

"Work? Uh, sure. I don't know how to do anything." It would have come out.

"That's all right, we'll train you. We work twelve-hour shifts. Will you work, or do you need the time to . . . write?"

"Oh, no, I'll work."

"Did you do any CTDs on *Oceanus*?"

"No." In this acronym-peppered science, CTD stands for conductivity-temperature-depth, which is what the device measures, and CTD has become the name of the device itself. I had watched CTD operations aboard *Oceanus*, but amid all that was new to me on the trip, I had gleaned little about its true function and importance to ocean science beyond the rudimentary fact that it collected water samples.

"Fine. We leave from Charleston on September 9th and return to Miami on September 23rd."

That was a lot easier than I'd reckoned. But September? This was 2005, that bad hurricane year. Here in June, we'd already had two.

"I know," said Chris, "I know. I'll pick you up at the airport."

I met the ship at the sprawling, nearly defunct Charleston Navy Yard, where kudzu vines climbed the sides of naked cinder-block buildings with black holes for windows, rain-rotted roofs falling in, a dreary place to call homeport. With a pilot boat, Coast Guard cutter, and a navy troop ship, the *Ronald H. Brown* was tied to a hardcore concrete wharf known as Pier Papa. Unofficial flagship of the NOAA fleet, the *Brown* is 275 feet from the stem of her pleasing upswung bow to her low, flat transom, and she carries her 52.5-foot beam all the way to the square stern. Like her sisters *Atlantis* and *Revelle*, built in the 1990s by Halter Marine of Moss Port, Mississippi, the *Brown* can crank out fifteen knots if she must, but at that speed, she inhales 350 gallons of diesel fuel per hour. Typically, she cruises at a more economical eleven knots, about thirteen miles an hour. At that stately pace she has crossed and recrossed every ocean and nearly every marginal sea on Earth from the High Arctic to the fringes of the Antarctic Ice Sheet. Greater speed would always be desirable, decreasing steaming time to the work site, but hardly possible for a vessel displacing 2,250 tons, riding 26.5 feet deep in the water, while toting a staggering tonnage of winches, cranes, and other heavy-duty machinery on deck. Also, the quality of data gathered by the array of hull-mounted ocean sensors to measure temperature, salinity, and current velocity while the ship is under way would be degraded by higher speed. Her long-legged range of 11,300 miles and sixty-day endurance (limited only by the quantity of food she can store) are more important than speed for her work.

Excited to be going to sea again on a research vessel, while feigning old-hand nonchalance, I paused at the foot of the gangway to take her in and savor the beginning. Though her working life was evident in dents and scratches near the transom where the heavy lifting is done, she's scrupulously maintained, and to my eye a handsome ship with a well-turned sheer, pleasing proportions, and bright white topsides. There was a problem, however, with the beginning. Hurricane Ophelia, a category-three that had been tearing up the Gulf Stream on its way north, had paused overnight as if to marshal its forces and make up its mind. NOAA weather was predicting that it would jink west for a direct hit on Charleston. We might be delayed a day. Or two. The captain, Chris said as he led me down the main deck corridor toward my cabin, was waiting until mid-afternoon to decide whether to hunker at Pier Papa or run for sea room. I followed Chris past laboratories port and starboard, and by the time we went around a couple of corners and down a stairway to the science berthing area somewhere beneath the waterline, I was totally disoriented.

"Since we're only doing CTDs on this trip, no mooring operations, there aren't many of us. So you get a cabin to yourself," Chris said, opening a door with my name on it.

There are fifty-nine berths aboard the *Brown* in nine single and twenty-five double cabins to accommodate her twenty-one-member operating crew, six officers, and up to thirty-one scientists. Mine was typical of the science berthing area, with a double bunk, two institutional metal chests of drawers and a hanging locker, frilless but comfortable, and best of all, I had my own en suite head with shower. However, Chris warned, "These forward cabins can be really noisy." He nodded toward my bed. "The bow thrusters are right over there on the other side of the bulkhead." I had already noticed industrial ear protectors stowed in the rack with the life jackets and survival suits.

Among other specializations, ocean-research vessels do most of their work when stopped, "holding station," while technicians and scientists probe the depths. Measuring the characteristics of a column of water, you need to remain over that column of water. The *Brown*, like *Oceanus*, has no rudder, no propellers in the usual configuration, and no steering wheel. Instead, she has thrusters and video-game joysticks. There are two thrusters in the stern mounted in dogleg nozzles that can be rotated 360 degrees in unison or independently. Two more thrusters are mounted in recesses on either side of the bow. A good ship driver can spin her in her own length, walk her sideways, and perform other moves normal ships need not, the most important of which is to remain in one place when and wherever necessary. The new Dynamic Positioning System, a sort of autopilot, helps in this by automatically firing the thrusters when necessary to keep her on station; all the bridge officer needs to do is inform the machine of the coordinates of his desired position.

"Come on, I'll show you around," said Chris. "Then I'd better go talk with the captain."

He led me down corridors, up companionways from deck to deck, around corners, into and out of the main lab, the wet lab, the hydro and biochemical labs, and finally the computer lab. "This is our home," he said about the latter. "This is where we run the CTDs . . . It's freezing in here. Why's it so cold?" We went up to the 02 deck to see the galley and mess room, or maybe it was the 03 deck, thence down below the waterline to the laundry room next door to the little gym. He showed me the ship's store, closed now, that sold snacks, sundries, *Ron Brown* shirts and other regalia. By the time we finished the tour, I couldn't tell the pointy end from the square end. Excusing himself to go see the captain about a hurricane, Chris recognized my disorientation. "We're back on the main deck. Outside is through that door right there."

I seemed to be in the way of the hustling deck crew, lifting aboard pallets of gear and provisions with a crane, while others bolted down the deck gear already aboard with practiced competence. Just another trip for them, while I was feeling that old rush of romance I've known since dock-rat childhood in the presence of seagoing ships and boats, but of course it's easier for us amateur, dilettante seamen to retain our nautical romanticism. For me, this trip was different from my first aboard *Oceanus* peering over people's shoulders, separate. Now, a worker, I was part of the team, even if I had no idea how to do the work. Still, I was in the way of the real workers out here. I watched for a time, wedged in the corner of the hanger, a covered area opening at the aft end onto the transom, until the bosun came along to fetch some heavy-duty lifting strops from a rack behind me.

"You want a hard hat if you're out on deck," he said, pointing to a row of them on pegs.

Pleased with the unique combination of hard-assed industrial seamanship and pure science that goes on aboard these vessels, I hung around for a while watching departure preparations. I introduced myself to a couple of the deck hands who had just returned from a survey of the Southern Ocean in the vicinity of Cape Horn, and I was pleased to learn that Mary O'Connell, a retired teacher who'd signed on to see the world, and Phil Pokorski, a former dive operator and lifetime boat pro, had read my book about Cape Horn in preparation for the trip. They thought I was a celebrity. When they returned to work, I remained in the way, my potent celebrity notwithstanding, so I re-racked my hard hat and went below.

Wandering back into the freezing computer lab, I met Carlos Fonseca, an affable technician/consultant on whose experience and intelligence, it would soon become clear, everyone in the science staff depended. Carlos is responsible for CTD operations from initial setup to final data processing and quality control, but his heart remains in São Paolo, where he raises canaries with his father. Introducing me to the CTD console, a computer and VHF radio in a carrel near the door, Carlos explained that my job would be to direct the winch operator by radio to lower the instrument to within twenty meters of the bottom—try not to *hit* the bottom, he stressed—and then bring it up, stopping at predetermined depths to fire sampling bottles and to record temperature, salinity, and depth.

Brad Parks and Guilherme Castelão, doctoral candidates at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS, pronounced "Rasmas") and engineer Ben Kates straggled into the lab talking about surfing. Old hands at this "CTD console watch," they commenced telling horror stories about screw-ups on previous cruises who had crashed the heavy, delicate instrument into the bottom. I pictured the explosion of silt and mud in the deep darkness.

I went out to have a look at this CTD I'd be endangering, strapped for now to a wooden pallet on the starboard side. They call it the "package" aboard this ship, since it contains a multitude of instruments to measure *C*onductivity, *T*emperature, and *D*epth. The package is huge. You have to stand on a stool or something to reach the top, and it weighs about a ton. Standing off, I could see only the gray plastic water-sampling bottles like skinny scuba tanks, twenty-three of them on this unit, mounted upright around the heavy circular frame. Kneeling, looking under the circle of bottles, I saw the array of instruments, the heart of the device, not a one of which I could identify. But I knew that their collective purpose was to determine the density of the water column from the bottom to the surface by measuring the components that determine density: salinity, temperature, and pressure. To learn the density—more precisely, the *differences* in density—along a particular strip of ocean reveals so much about the nature and extent of ocean motion that CTD operations are included in every cruise no matter its overall purpose.

Temperature is by far the most potent participant in the density mix. Cold water is denser (heavier) than warm water, just as cold air is heavier than warm. And since water and air are both fluids, they behave according to the same broad physical laws, the most broad of which states that warm fluid rises while cold sinks. Somewhere inside the circle of "Niskin" bottles, among the cables and connectors and instruments, there were two temperature sensors capable of measuring heat to a high degree of accuracy and reporting their readings in real time to our computer in the lab.

Salinity is the total quantity of dissolved solids contained in the water, including sodium, chlorine, calcium, magnesium, sulfur, about eighty in all, some in minute quantities. Rivers and rainwater runoff from land constantly pour more sodium and chlorine and other "salts" into the oceans, but this doesn't alter the total salt content because input is balanced by the tendency of heavier materials to sink to the bottom without dissolving. Salinity, therefore, has reached a "steady state." However, like temperature, it needs to be measured within fine tolerances. The total range from highest salinity to lowest is the difference between 33 and 38 parts per thousand. However, in more than seventy-five percent of the ocean, the salinity ranges between only 34.5 and 35 parts per thousand. In the old days, you had to boil off all the liquid in the water sample, then chemically analyze the solids left behind, a tedious and imprecise process. Late in the nineteenth century, the German chemist William Dittmar discovered that, while the quantity of salt constituents vary from place to place in the ocean, their ratio one to the other remains constant. This meant that you could measure only one constituent of salinity, usually chlorine, and extrapolate for the rest, an improved technique at the time, but an antique today.

In 1948, Henry Stommel wrote, "Due to the fact that water in the ocean is a conductor, and that it is everywhere under the influence of the earth's magnetic field, we should expect . . . that wherever the water is in motion electric potentials and currents will be established." To put it simply, when ocean water moves, it produces a slight electric charge. Since the electrical charge could be easily and accurately measured by adapting a common conductivity meter to survive a deep swim, oceanographers searched for a stable relationship between conductivity and the chemical constituents of salinity. When they were finished, they found that they didn't need to bother with chemical analysis at all. By applying an algorithm, they could accurately calculate salinity based on conductivity alone. And now conductivity readings, like temperature, are transmitted via the conductor cable directly to our computers.

Pressure, the other important element in the density mix, is a function of depth, a measure of the weight of water above a certain depth. This matters because seawater is slightly compressible, and when anything is compressed, a certain quantity of heat is generated. (That's the basic principle behind the Diesel engine.) The amount of pressure-generated heat needs to be learned so that it can be subtracted from the actual temperature.

As to this business of density, the normally recalcitrant ocean is remarkably cooperative. A water mass acquires its temperature and salinity signature at the surface, and when it sinks, as in thermohaline circulation, it maintains that characteristic combination of temperature and salinity as it moves about the ocean at depth. This, of course, allows scientists to follow its travels by identifying its "T-S profile."

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"We're going," said Chris entering the lab. He looked at his watch. "At 1500. That's two hours."

What about Ophelia?

"It's veered a bit north, now predicted to hit Cape Hatteras tonight." The original plan had been to steam southeast from

Charleston directly toward the offshore end of the study line about three hundred miles east of Abaco Island and then work back westward along that same line of latitude (26.5 degrees North), CTD-ing all the way. Now, however, a southeast heading would present the ship's beam to Ophelia's hurricane swells. The motion would be untenable, gear and people careening from side to side in the deep rolls, a truly ugly and dangerous prospect. "The captain wants to run south, keeping the seas on her stern until we can turn safely east. It'll be plenty rough for a couple of days. So what we need to do is lash everything down in here and in the main lab. Okay?"

"Why's it so cold in here?" Brad wanted to know, pointing to a digital thermometer that read 55 degrees.

"Yeah, I'll ask somebody to look into it."

Chris assigned the lashing job to me, figuring that as a sailor, I probably knew a thing or two about lashing. He pointed me to a spool containing a couple of miles of cord and said I should use it all if necessary, just so nothing moves. Boy, did I lash. Feeling the engines rev, I took a break and went topside to watch us get under way. Everything that happens on deck, as separate from the engine room and the bridge, is the bosun's province, a capable man in this case clearly respected by the crew, with a Stetson-shaped hard hat and Maori tattoos ringing both legs. Line handling and the rest all deftly done, we steamed away from the pier out into the brown water of the Cooper River, heading toward the Route 17 Bridge. The captain had waited for low tide in order that the towering masthead array of atmospheric sensors, Doplar radar pods, navigation receivers, and long-range communication antenna cleared the bottom of the bridge span. Little harbor porpoise played in the bow wake as the *Brown* accelerated into the main channel. We passed the battleship *Yorktown* and a World War II submarine docked at the island museum on our port side. Fort Sumter came into sight, a vague lump in the muggy haze, away to starboard. The confluence of two rivers, Charleston Harbor is broad but shallow, and the channel is still carefully marked with red and green buoys over a mile offshore. A long swell from the northeast finally signaled deep water.

Co-chief scientist Lisa Beal came on deck from the computer room, judging by her unseasonable wool sweater and hat. "We're going to have to live with it, I hear. Something's broken, and they can't fix it. We'll all get ice-cream headaches." Chris was trying out a new watch schedule, from 2 p.m. (1400) to 2 a.m. (0200), and Lisa was in charge of the second watch, 0200 to 1400. (Thankfully, I had drawn the first watch.) But, she explained, her main responsibility was the so-called ADCP, the Acoustic Doppler Current Profiler, and apparently it wasn't working up to snuff, if at all. I couldn't make out which because I wasn't too sure just what this ADCP was all about.

"It's another means of measuring deep current. You've probably heard the way the pitch of an ambulance siren changes as it speeds past. That's the Doppler shift. The ADCP senses ocean currents by bouncing acoustic waves off particles such as sediment or plankton drifting with the current. The wave arrives back at the instrument with a slightly different frequency than it went out with, and the difference tells us how fast the particles are moving. Oh, look, dolphins . . . Have you seen the ADCP?"

She led the way down the stairs from the elevated bow to the low main deck on the starboard side. Lisa knelt beside the CTD package and pointed to a three-foot-long yellow cylinder with four ceramic heads protected behind an epoxy lens aimed downward mounted among the rest of the stuff under the ring of Niskin bottles. This, she explained, was a "lowered ADCP." Like all the larger research vessels, the *Brown* carries another, a "shipboard ADCP," mounted in the hull peering downward. "This is useful because it can do its work while the ship is under way steaming between CTD stations. The drawback is the shipboard ADCP can only profile the ocean to a depth of 750 meters, while the average depth is around four kilometers, and that's where the lowered ADCP comes in."

Lisa didn't seem so fond of her lowered ADCP.

"It's great when it works."

There was a wooden picnic table aft on the starboard side in the shadow of the big main winch and its operator's house. Ben and Brad were sitting on the table talking longingly about the gnarly storm waves they were going to miss back in Miami. Brad was carrying, as he would through most of the trip, his copy of Joseph Pedlosky's famously difficult *Geophysical Fluid Dynamics*. "Have you read it?" he asked.

Afraid of the math, I had avoided the esteemed edition. The laws of physics determine the ocean's motion; the language of physics is math. I don't do math.

Guilherme Castelão, a bright, intense Brazilian who was dealing with these thorny concepts and their equations in a second language, would tell me later that "without math, I can't prove you anything." Luckily, I had nothing to prove.

Carlos and Chris came on deck followed shortly by Jon Molina, a RSMAS tech on the second watch who was to help Lisa collect and compile the ADCP data. Now the entire science staff had gathered around the picnic table. This cruise was part of an ongoing project called the Western Boundary Time Series (WBTS). Once or twice a year since 1984, scientists from AOML and RSMAS have been measuring the ocean dynamics along the same line of latitude, 26.5 degrees North. That study line—which cuts the Florida coast near Fort Lauderdale and extends eastward through Abaco Island several hundred miles out into the Sargasso Sea—was chosen by the AOML/RSMAS oceanographers partly because of a happy coincidence. Nearby, the telephone company had strung a cable along the bottom to connect Florida to the Bahamas, which, while performing its intended purpose, incidentally measures the voltage induced by the passing water. Applying some math to the voltage numbers, the scientists can calculate the water transport in the Florida Current, and so the cable happens to afford the Miami oceanographers a cheap but useful "time series" profile. However, the choice of 26.5 North as the focus of the Western Boundary Time Series was based on broader oceanographic considerations. The western side of the Atlantic at that latitude is richly dynamic. First, the warm Florida Current portion of the Gulf Stream crosses it from south to north. Also, along the seaward side of the Bahamas another piece of the Gulf Stream gyre, the relatively weak Antilles Current, flows northward until it merges with the Gulf Stream north of the Bahamas. And then, of course, there is the cold Deep Western Boundary Current flowing in the opposite direction beneath the Antilles Current. That profusion of flow, shallow and deep, warm and cold, makes this strip of ocean as relevant to the transport of heat, and therefore to climate, as any in the hemisphere.

At some point, we were going to retrieve a malfunctioning, inverted echo sounder, an acoustic device designed to rest on the bottom and measure the temperature and salinity of the water passing overhead. We would also deploy some drifters, Chris said, simple surface floats equipped with a temperature sensor and GPS receiver. Since CTD work was the main point of the cruise, we didn't need anymore people than could comfortably occupy a picnic table. We watched the low-lying Carolina coast fade to a wavering smudge on the western horizon, and the *Brown* powered through a long, ominous swell rolling in from the northeast out Ophelia's way. It might be worse tomorrow.

"Well, it's that time," someone said. "Dinner." It was 4:30. One gets used to it.

Throughout much of the cruise, Chris and Lisa generously held fizzo lessons for me. At my request, the first night's lesson was "Geostrophy 101." Geostrophy was another of those fundamental

principles of ocean behavior I'd never heard of before I began trying to see the ocean through oceanographer's eyes. And at that time, September 2005, vision was still blurry.

"Remember, Ekman transport piles up water near the center of the gyre, and gravity takes it away," said Chris. "So geostrophy is a steady state in which the pressure gradient and the Coriolis force fall into balance." He wrote it as an equation: (1 / rho) dp / dx = *f*v. "Oh, that's right, no math."

"Sorry."

"'Geostrophy' is borrowed from meteorology. The hill in the ocean is basically the same as a region of high pressure in the atmosphere. Air wants to flow away from the center of high pressure outward toward regions of low pressure, but Coriolis bends the flow to the right in the Northern Hemisphere, and the winds then spin in a clockwise direction along lines of equal pressure. Same thing happens in the ocean. Look at it this way: I'm standing in a boat at one point in the ocean, and you're standing in another, say, sixty miles away. Suppose the sea surface is one meter higher under your boat than it is under my boat. That means there is more water under you than me, and so there will be a pressure gradient between us. Water will want to flow from beneath your boat towards mine. Now because of Coriolis, the flow will be turned to the right, so in effect the current will flow perpendicular to the line of sight between our boats. Our purpose is to measure the slope of the pressure gradient in order to learn the velocity of the current. That's where the CTD comes into it. The CTD measures salinity, temperature, and pressure. If we know those things, by applying a couple of equations, which I won't mention, we can calculate density. By comparing the density between this CTD station and the next one and the next, we're able to measure the slope—the horizontal pressure gradient—between them. If we know that, we can calculate the flow between stations, arriving at the so-called thermal wind equation. If we run about fifty stations, like we're doing on this trip, across a specific strip of ocean, we get a broad picture of the current. But then we have to do it again six months later and six months after that to make sure we're not mistaking temporal variations for the mean flow. That's what this Western Boundary Time Series Project is all about. We've been measuring this strip of ocean since the early eighties."

That was clear enough. From the CTD data, you can learn the differences in density between stations, and from that information you can calculate the current's velocity without having to measure it directly. Right?

"Well, yes," said Lisa. "But it's not quite that simple."

I was afraid of that.

"After we do the math, we still don't know the absolute velocity of the current. We only know the relative flow between the measured stations."

Yes, I'd read about that. "Is this the reference-level problem?"

"Exactly," said Chris.

Lisa said, "The density gradients in the ocean can tell us how geostrophic velocity varies with depth, but it can't tell us the absolute velocity—because we can't measure the actual sea surface slope. What would we measure it against?"

As Chris put it, "If the material that makes up the Earth were perfectly uniform and Earth were perfectly spherical, then in order to talk about sea-level differences we would need to measure sea-height relative to a circle that is everywhere equal distance from the center of Earth." The problem for oceanographers is that Earth isn't entirely spherical, and the material comprising Earth's surface is not uniform. There are mountains in some places, valleys in others, and a lot of ocean everywhere. Scientists have long struggled to find a level surface or something to represent it—the so-called geoid—that could perhaps be measured from space by satellites, but at this writing, everyone agrees, the range of error is too great to be completely reliable. The geoid is sort of an idealization, and reckoning a level surface remains tricky.

Over the years, Lisa pointed out, oceanographers have tried myriad ways to "reference" geostrophic velocities: various kinds of neutrally buoyant floats, moored current meters, shipboard and lowered ADCPs, bottom-mounted pressure sensors, and so on. But all these methods have a similar problem, the same one we've "referenced" earlier, that is, the constant variability of the ocean's circulation. The geostrophic currents, those calculated from CTD measurements, are being constantly confused by small-scale perturbations from, for instance, tides and other waves bouncing around through the interior of the real ocean, what scientists call "noise."

So what's the poor oceanographer to do?

He or she tries to determine a "level of no motion" or "reference level." Chris explained that early oceanographers just assumed that the current velocity at the bottom of the ocean was zero. But as time passed and technology advanced, they learned that the deep ocean was indeed moving, so they had to look elsewhere for their level of no motion. Once scientists learned to identify individual water masses by their temperature-salinity signature, they found points where one water mass was flowing north, for instance, while another, deeper mass was flowing south. It stood to reason, then, that there should be a point of zero velocity between the two masses, and that point could be found by detecting changes in temperature and salinity. That determination works in places where adjacent water masses move in distinguishably different directions, but that's not the case everywhere in the ocean. In some places, as we've said, the so-called surface current carries all the way to the bottom. And in other places, the water masses move with uncooperative variability in relation to each other. For instance, time-series measurements along 70 degrees West, the longitude of Cape Cod, show that while most of the time the Deep Western Boundary Current flows in the opposite direction from the Gulf Stream, it doesn't always. Occasionally it changes direction as well as depth. There may still be a level of no motion somewhere in the mix, but it's hard to find because it moves around and up and down.

"So how do you solve the reference-level problem?"

"You can't entirely," said Lisa. "There will always be a degree of uncertainty in the geostrophic velocities, but our objective is to reduce them as much as possible. That's one of the reasons why we measure this 26.5 North line twice a year. Where we have moored current meters in place over the long term and, say, repeated ADCP measurements, we gain a pretty accurate idea of the actual current. We can use those places where we know the current as benchmarks to figure out a level of no motion with simple arithmetic. It's not one hundred percent accurate, but we can get close. Occasionally we just have to take an educated guess and say, okay, three thousand meters is our level of no motion. Over time," Lisa said, "we can refine our assumption or find a better one."

"So theoretically, if you put current meters on moorings all over the ocean, you wouldn't need the CTDs?" I asked.

"Theoretically, yes. But there aren't enough ships and oceanographers in the world to tend all those moorings even if somebody agreed to pay for them," said Chris.

"And still," said Lisa, "you'd have to come out here, say, once a year, to replace the batteries. Besides, current meters need to be pulled out of the water and taken ashore for servicing and recalibration from time to time. The conductivity sensors, for instance, which measure salinity, lose accuracy over time. So we have to take water samples with the CTD bottles and analyze the salts in order to know how to recalibrate the current meters."

"Where do you analyze the salts? Back ashore in the lab?"

"No, we'll do it right here aboard. Have you seen the salinity lab?"

I hadn't.

"It's this little closet just across the corridor. No place for those prone to seasickness. In fact, when you get up to speed on the CTD console, I'll have Guilherme run salts, and you can do the CTD alone."

Oh. I didn't really want that responsibility, but then that's why I was aboard.

"Don't worry, you'll be an expert in no time."

"All you need to remember is—"

"Don't hit the bottom. I know, I know."

Oceanographers like it when outsiders seek to understand their work. Since much of this country's oceanographic research is paid for by the National Science Foundation and NOAA, supported in turn by taxpayer dollars, scientists are, to some extent, obliged to speak to the rest of us. They call it "outreach," and everyone I met approves of the concept, but in practice outreach is problematical on a couple levels. To translate esoteric principles into popularly understood language without draining the integrity from the principles requires pedagogical technique, not part of the research scientist's job description. Then there's the "forum" question. Where would this pedagogy take place? I can't picture my fizzo friends calling a news conference to report their research findings, to keep us posted as it were, short of something really dramatic. That they don't keep us posted and that we don't ask that they do so have provoked a level of confusion as to what, actually, is going on in ocean and climate science. For instance, these same scientists from RSMAS and NOAA who are working jointly on another ocean/climate project have had to draft a press release to clear up the murk generated by a string of erroneous press reports. They had to say in effect, no, we're not talking about the Gulf Stream shutting down. But oceanographers aren't yet used to their new relevance and its attendant relationship to publicity. Lisa, Chris, and other young oceanographers said that ten years ago they would never have imagined that the press, let alone the public, would want or need to hear from them.

Also militating against organized outreach, the culture of science doesn't reward those who try to address the public. I suppose things have lightened up in this respect since fellow physicists excoriated Carl Sagan for his television series *Cosmos*—particle and theoretical types going around saying mockingly, "*billions* of stars"—but such efforts are still faintly disrespectable. Maybe this exclusive spirit will evaporate as oceanographers absorb their new role—or as we absorb the relevance of their research. But scientists will still need to maintain their professional skepticism, and it's not exactly fair to ask them to become advocates for, say, emission caps on greenhouse gasses. Advocacy and intellectual objectivity are hard to reconcile. Also, political advocacy, at least for now, is professionally injudicious for a scientist whose funding proposal might be judged yea or nay by someone who disagrees with the position advocated or disapproves of advocacy, period. This, I'm told, is less a factor in climate science, since there are no climate-change dissenters among real scientists, only those who dislike the language and syntax of the present climate-change "debate."

Be that as it may, Lisa and Chris were reaching out to me beyond the call of duty. This level of time and concentration would be available only here aboard ship. I hoped to be a quick study, but I felt like going outside to make sure the ocean was still there. We could feel its actuality in the windowless lab, the *Brown*'s stern rhythmically rising to the following seas and sagging back. (There are several large portholes in the lab's outboard wall, but these are routinely covered at night with blackout plates to prevent light spill that might interfere with visibility from the bridge.) And occasionally we could hear the ocean wash along the starboard side, but I still wanted to go outside and look just to be sure. Fading, we concluded the lesson

about midnight. I walked out on the transom, stepping gingerly around various objects and shin-cracking protuberances barely visible in the shadowy light spilling from the hanger, until I remembered I had a flashlight in my pocket. Alone out there—everyone else who wasn't on watch was asleep or watching *Meet the Fockers* in the crew lounge—I stopped six feet from the lifelines strung across the stern for safety's sake.

Marble-sized globules of green phosphorescence churned in the white wake. The moonlight, bright and shimmering two hours ago, was diminished now to a dull loom near the top of a towering black cloudbank. I panned my light across the wake searching for a sense of the sea state that I could correlate to the wind, but the puny beam illuminated nothing. I longed for something from the ocean. I distracted myself for a while concentrating on the seeming dissonance between the scientific explanation of the ocean and the other more personal, evocative view unexpressible in the language of physics. I knew this same vague longing as a kid scuba diving in the Gulf Stream and earlier, a child standing on a Florida beach in late-afternoon shadow, and it has been aboard with me on every ocean trip since, particularly at night when the ocean reveals almost nothing of itself. As a child, I dreamed of living in the ocean, drifting through the mid-water where sunlight barely penetrates in a sort of particulate suspension to watch ocean creatures materialize from the gloom, pass, and disappear again. Clouds pinched off the loom of the moon.

"Do you need some light?"

I jumped.

"I saw you out here on the screens from the bridge." It was Lieutenant Elizabeth Jones. "I came down to see if you needed light."

Since there were no unobstructed sightlines from the bridge to the transom or the side decks, the ship was being scanned constantly by video cameras. I knew that, but it hadn't occurred to me that my presence on the transom would excite concern on the bridge. Just being here, I had made Liz trek down numerous flights of rolling stairs to see if I needed light. I apologized for the inconvenience and said that I was just looking.

"Well, if you need anything, you can call the bridge from one of the telephones. Just dial 125."

"Thank you."

"No problem."

Next morning, we were in the Gulf Stream. It wasn't necessary to see the water to know that. Humidity signaled its presence. Several engineers standing around in the hanger having coffee and a smoke ignored me as I passed through their conversation onto the open transom. The Gulf Stream is blue, as everyone knows, but there is no other blue like it in nature. It's not a light-hearted hue like the blue of a cloudless sky on a June morning, but dark and dense, more sensation than color, as if consciously, artistically designed to evoke extravagant response. *Gulf Stream* blue.

Removing myself to the starboard quarter (the right rear corner of a ship), beneath the boom arm of the big black crane I watched those straight shafts of sunlight shimmering down into the depths. Actually, the water isn't blue at all, but gin-clear, transparent, due to near absence of organic material in suspension. Blue is the collaborative trick of water and light. When sunlight penetrates the surface, the water strips the spectrum of reds and greens and yellows, leaving behind only the blue. But the trick doesn't diminish the evocative power of this Gulf Stream blue, and the feel of the heat engine running full blast affirms its power. A deckhand climbed into the driver's compartment and fired up the crane engine. He leaned out the window to ask me to move before he swung the boom arm inboard, but I was already on my way.

Chris Churylo, taking the air on the transom before his shift began, introduced himself, and when asked about his role aboard, said, "If it has electronics, it's mine to repair and maintain—radars, computer networks, communication, entertainment, and science equipment." That seemed a lot for one man to know. He didn't actually *know*, he said, but he could read a manual.

The hurricane avoidance plan had been to carry on south to about 28 degrees North, the latitude of Cape Canaveral, Florida, before turning east toward the survey line. But Chris had just heard that, since the seas weren't as bad as suspected, we might make the eastward turn seventy miles or so north of that latitude at around 1500 today. He had heard, also, that a tropical storm named Rita was expected to turn into a hurricane by midnight and head west, passing between our survey line and Cuba in the next several days. Had he heard anything else?

"There's going to be a surprise abandon-ship drill before lunch."

I went below to my cabin to check my assigned muster station posted on the door for abandon-ship and fire drills just as the claxon went off and an intercom-voice said, "Abandon ship, abandon ship. All hands report to your abandon-ship stations. This is only a drill. Repeat: this is only a drill." Yes, but it's taken very seriously indeed aboard these vessels. I put on a long-sleeved shirt and hat, as required, collected my immersion suit and life jacket and made my way back up the stairs to our assigned place at the after end of the main lab on the starboard side.

James Brinkley, a tall young ensign uniformed in crisp khaki, was in charge of the science abandonees. He asked Meinen to count heads, and when that was complete, Brinkley informed the bridge that we were present and accounted for. James told us to don life jackets, make sure that there was a whistle and strobe light attached and that the strobe worked. Then, with apologies, he told us all to climb into our Gumby suits, and we waddled around for a while sweating profusely as James checked us out. "Any questions?"

"Secure from abandon-ship drill," said the voice from on high. "Prepare for man-overboard drill."

Uninvolved in that, Chris, Lisa, Brad, Ben, Carlos, Guilherme, and I sat around on the picnic table to watch. A crewman carried a life-size dummy named Oscar in a Gumby suit and red helmet onto the transom and waited for radio instructions from an officer. When they came, he heaved Oscar over the side.

"Man overboard!" said the intercom voice. "Away on the starboard side."

As she slowed to a stop, four crewmen rushed up the stairs to the O2 deck and clambered into the boat, descriptively called a rigid-hull inflatable, or RHIB, slung outboard from the O2 deck on an ingenious hoist. The winch driver lowered the RHIB into the water, and it sped away toward the MOB, a speck in the distance, appearing and disappearing with each wave. The sobering lesson—*stay on the ship*—was not lost on the picnic-table audience. Everyone involved in the recovery knew the drill was coming; the boat crew was geared up and ready; the ship had stopped immediately, but the MOB dummy was already so far astern we had to stand on the table to see it in fleeting glimpses. Without a life jacket, a real man overboard would be in serious trouble, even in these warm waters; a man or woman who went over the side at night would likely become part of the deep-ocean circulation we were out here to study. Later, I asked around to learn whether anyone had ever been lost off the *Brown*. Apparently not, but the question brought up the "swim-call story."

"Swim call?"

At the captain's discretion, research-ship personnel were allowed to take a swim while the ship was stopped, "vastly agreeable in these torrid zones," as Captain Ellis put it a couple of centuries ago. That

policy was terminated not long ago when during a swim call somewhere in the equatorial Pacific, a tiger shark removed a scientist's leg in a single pass. "She survived, but swim call didn't," as someone put it.

The captain made his left turn toward the east before dinner, and the seas, seemingly negligible when they were on the stern, set her rolling as they passed under her port beam. Shortly after dark on the second night out, still short of the study line, the *Brown* came to a stop. We were going to make a practice CTD cast. The main purpose was to test the salinity and temperature sensors and the ADCP return, secondarily to teach the volunteer to make himself useful. When Carlos and Chief Survey Tech Jonathan Shannahoff donned life jackets and hard hats and headed out to launch the CTD, I followed them onto the open starboard-side deck.

Carlos double-checked the connections and the arming mechanisms on the bottle caps, and when he signaled all was in order, Jonathan radioed the winch driver, out of sight one deck above, to take it up. Carlos and Jonathan steadied it by hand against the building roll until the winch operator swung it outboard, and Jonathan ordered the winch to dunk the package. I returned to the computer lab to learn my new job. While I had expected to watch over someone's shoulder, Carlos asked me to take a seat at the controls, which consisted of a computer screen and radio mic to talk to the winch driver.

With the package awash just below the surface, it would be up to me to make sure all the sensors were working. "Okay," said Carlos, peering at the screen "everything is fine," though I couldn't tell how he knew that. "Now tell the winch driver to take it down to ten meters. Just say, 'Winch, down to ten.'" I did so, authoritatively. "We wait at ten meters for two minutes to let the instruments adjust, then tell the winch to take it down at thirty meters per minute."

"Down at thirty, please."

Mary, the winch driver, clicked the mic button twice as acknowledgment. (We're instructed by Jonathan not to converse with the winch person even if we're buddies, stick to business.) We watched the depth increase. At one hundred meters, we increased the speed to sixty meters per minute. The CTD measures pressure instead of depth in a unit called decibars, but "d-bars" coincide closely with meters. Carlos switched to another computer screen that registered in the form of a line graph changes in temperature, salinity, and pressure with a different color for each. This visually revealed the broad stratification of the ocean.

As Ellis and others noticed centuries ago, the Sun warms directly only the uppermost sliver of seawater. Solar heat is churned deeper beneath the surface by wind-driven waves, resulting in a well-mixed layer with constant temperature and salinity, but seldom below three hundred meters and often no more than seventy-five meters. This is called straightforwardly the "mixed layer." Below the mixed layer lies the "main thermocline," ranging in depth from two hundred meters to as much as one thousand meters, depending on local conditions. Temperature decreases rapidly in the main thermocline. Beneath the thermocline, in the deep layer, temperature remains nearly constant (cold) all the way to the bottom. The visual representation of the ocean layers appears on the monitor in the shape of a champagne glass—straight down from the lip, bending inward, then straight down the stem—as the package passes down through the mixed layer, thermocline, and into the deep layer, respectively. "That's what you look for on the downcast," said Carlos, "that champagne shape." He pointed to another instrument in a bulkhead lined with instruments and black boxes called the "bathy" that acoustically measures the bottom depth. We were in 4,450 meters of water, according to the bathy on the bulkhead. "You want to stop the package twenty meters above

the bottom, but don't use the bathy for that. I show you when we get there."

Brad and Guilherme wandered off as the package proceeded through the lightless depths. I stayed and watched the layers resolve, pressure increasing as temperature decreased. Jonathan bustled nervously around the bank of instruments. Lisa joined him and they watched skeptically as the ADCP data came in. Something was amiss, but I never learned just what. As the bottom approached, Carlos told me that there was a down-looking altimeter mounted on the package, and it would kick in at 250 meters above the bottom. If it doesn't, he said, I should stop everything and call him or Chris. An hour or so later, the altimeter had dutifully joined in, and the CTD, it said, was one hundred meters above the potential crash site.

"At forty meters, tell Mary to stand by, and she'll slow to thirty meters a minute."

"Winch, stand by."

"Standing by," she replied.

Chris joined us and sat down behind me. "Don't think I'm paranoid or anything," he said.

"Make sure that she actually does slow down," said Carlos pointing to the decreasing altimeter numbers. "Then at twenty meters, say, 'aaaaand stop.'"

I said so, and it stopped after bouncing for a bit on the long cable.

On a standardized form, the "CTD Log sheet," Chris had listed about a dozen bottle-stop depths. The water is sampled on the way up, of course, because if you closed a bottle on the way down, the pressure would crush it flat. (Among the amusements apparently universal on research cruises is to write greetings to friends ashore on Styrofoam cups and send the cups down with the CTD; they come back up squeezed to thimble size.) Adhering to radio protocol, I was to stop the package at each depth, record temperature, pressure, salinity, and then "fire" the bottle with a mouse click to close the bottle stoppers trapping in situ water.

"And that's pretty much it," said Carlos. "Make sure you fill out all the information on the sheet for each bottle stop. Let's see, I'll show you how to log off the computer and shut down the package when it comes up. What else?"

"Don't hit the bottom."

"Yes. Don't."

A few minutes before our watch ended at 0200, Chris asked me to help him deploy the first of a series of "drifters," and I followed him out to the hanger where they were stored in stacked cardboard boxes. Simple inner-tube size floats, Chris explained, drifters are an inexpensive means of measuring sea surface temperatures (SSTs). Satellites do this most efficiently from space, but direct measurements by drifters and things are used to validate (or invalidate) satellite readings. Scientists are keeping a sharp eye on SSTs, because rising surface temperatures mean increased evaporation that pours more moisture into the atmosphere and, in turn, leads to more severe storms among other feedbacks. And then there's the matter of sea-level rise: Heat causes water to expand—"thermal expansion" is the straightforward technical term—so if SSTs rise, sea levels will rise as well.

Drifters also measure surface current velocity, Chris was explaining. "Well, not literally the surface, but fifteen meters down. It carries a sea anchor—we call it the holy-sock—to keep the drifter from riding with the wind rather than current." Above water, it carries a GPS-style receiver that updates its position several times a day, and from the changes in position between fixes, current velocity can be easily reckoned. Chris phoned the bridge, where every activity is logged, to inform them that we were about to deploy the drifter. We carried it, about the size of a coffee tabletop, out to the stern, where I began opening the box.

"That won't be necessary," he said. "We just toss the whole thing over the side. The cardboard disintegrates, leaving the drifter to do its work. Ready? On three?" The box disappeared into the darkness.

I humbly agree with John Swallow that the purposeful structure and repetition of shipboard life clears the mind, affording new perspectives on shoreside life. I, for one, love shipboard routine, its orderliness and efficiency, watch-on–watch-off, no matter what, twenty-four hours a day. Others would rather not go to sea for that same reason. Mealtimes are fixed. The evening meal is over at 5:30. I never eat three meals a day at home; out here I wouldn't miss one, in addition to our ritualized post-watch snack. The galley itself is off limits, but the mess-room pantries are always open. We eat, sleep, and run CTDs for twelve hours and repeat the process. I was tense the first time running the console by myself, but I didn't bury the package in the bottom, and by my third cast—the deep casts took three hours to complete—I had the hang of it. At the completion of each cast, with the package lashed aboard, Guilherme, Carlos, and I go out to extract water samples, one round for oxygen, one for salts, and the deeper into our watch, the funnier our own patter seems to us. I've noticed on sailboats as well as these research vessels that a "trip joke" inevitably evolves, and we find it endlessly hilarious even as we run it into the ground (deck). But it's impossible to retell to those ashore. I used to try, but no longer. Trip jokes make no sense except to those who were sampling salts and oxygen at 0100 in 25 knots of wind, their ankles awash on a rolling deck. I miss the jokes and the shipmates and the ocean when the trip is over.

At sea, weather, which is to say wind, determines the sea state (waves) and thereby the quality of life, and so a flutter of excitement ran through the science staff when Chris Churylo passed around the latest NOAA Tropical Weather report. Rita had indeed matured into a category-three hurricane, and was heading west northwest at

20 mph. I plotted the coordinates of its reported position on my chart and compared that to our present position. It was heading right for us. Hurricanes focus people's minds when floating in their paths. I measured the distance between it and us. If Rita maintained that course and speed, she'd be on us the day after tomorrow. We went back to work dipping and retrieving the package. I admit to a certain curiosity about how the *Brown* would behave in really heavy seas, but that's not something someone in the moment says out loud. Swells from Rita's direction were already changing *Brown*'s motion. (The lab never warmed up; we wore four layers and foul-weather jackets at the console, then took it all off to go outside to sample salts and things in the path of a hulking subtropical disturbance.)

By the afternoon, September 19, NOAA's weather update reported that Rita had turned due west, now predicted to pass through the Old Bahama Passage between the lower arm of Great Bahamas Bank and the north coast of Cuba. Only its fringes, tropical-storm conditions, would brush our position out on the 26.5 North line. By dark, we were experiencing 30-knot winds with higher gusts and spectacularly beautiful seas, though I would not have used that word had we been aboard a 40-foot sailboat. The *Brown*'s decks were constantly awash, and the package was swinging wildly, threatening its own well-being and ours, when we hoisted it off the deck. By 2100 (9 p.m.), Chief Survey Tech Jonathan Shannahoff had seen enough and called a halt to operations. Heartbroken, our watch played poker until 0200, for funzies, no gambling allowed on NOAA ships. Routine resumed the next day in sparkling sunshine, no wind, but a residual southerly swell kept us moving from handhold to handhold.

CTD ops were suspended for several hours on the 20th in order to retrieve one of Chris's Inverted Echo Sounders (IES). "Observational" oceanographers like Meinen are in the business of figuring out how to measure the ocean, what combination of instruments might best gather the desired data, and then going to sea to gather it. Think of the IES, he said, like a stereo speaker keyed to a stopwatch. The IES sits on the bottom on an expendable metal rack and shoots sound pulses up at the surface that then bounce back to the instrument. When it emits a pulse, it starts the stopwatch; the return pulse stops the watch. These many thousands of "travel-time" measurements provide information about the total heat content of the water because the speed of sound in seawater is a direct function of water temperature. Chris conveyed instructions via computer to the acoustic releases telling them to let go of the rack, and they obeyed. About an hour and a half later, Mary spotted the strobe light pulsing on the black surface, and an hour after that, we had hooked it back into human hands.

Starting at the farthest seaward point on the 26.5 North line 274 nautical miles east of the Bahamas, we did some forty CTD casts, working westward watch-on-watch-off. Ten days later, by the watch change at 0200, we could see intermittently between passing squalls the dull loom from two lighthouses on Great Abaco Island. The plan was to run CTD casts on through the Northwest Providence Channel and then across the Florida Straits right up to the continental shelf off Ft. Lauderdale. I was surprised to learn, however, that before we could work in Bahamian waters, we would be required to clear customs. This would take at least half a day. *Brown* stopped tantalizingly close to the seaward edge of the coral reef off Abaco Island where the salmon-colored water turned abruptly deep blue. The executive officer, with our passports in a waterproof packet under her arm, joined the boat crew already aboard, and they lowered away. A hot southwest breeze was kicking up little steep waves too tightly packed to fit the boat between the crests; its crew would have a molar-jarring ride to the customs office. Meanwhile, members of the science staff peered down into the gorgeous azure water.

"Swim call!" someone shouted wishfully.

"Perhaps we could sign a shark waver."

"Sure, you write it up and take it to the captain."

Five hours later they retrieved the RHIB with its wobbly complement, and we got under way into the Northwest Providence Channel, the deep trench through the middle of the Bahama Islands. After dinner, we had the CTD back in the water.

The stations came fast and furiously in the shallow continental slope water, none deeper than eight hundred meters. The ship headed for the next stop the moment we had the CTD back on deck. By the time we'd extracted our oxygen and salt samples, emptied the bottles, and rearmed their triggers, she was maneuvering into position for the next cast. We'd been hoping that the shallow-cast rush would fall to the other watch. By midnight, we could see headlights turning onto A–1A in Ft. Lauderdale. By 0200, the last cast—the fifty-fourth—was complete. Our work was finished. The *Brown* turned south and we headed for Government Cut, Miami, and the Coast Guard dock near South Beach. I don't like the endings. I'd grown weary with CTD routine, like everyone else, but I wouldn't have minded a few more days at sea.

I walked forward to the point of the bow and stood for a time watching Broward County slide by and growing nostalgic. I grew up on that coast and fell under the ocean's spell; my mother had died there several months earlier. But I decided not to dwell on nostalgia, turned aft, and joined the science staff telling stories in our arctic lab while wearing coats and woolen caps. A couple of hours later, after waiting her turn out by the sea buoy, *Brown* steamed into Government Cut. Gathered along the starboard rail, we watched the pastel neon on the deco hotels behind Lummus Park and the hot discos at the foot of Ocean Drive. Lisa, who lives there, named them for us. Nikki Beach Club, with the South Sea motif, that was *the* place for Sunday-night partying on the beach beneath the firmament or in teepees, cabanas, beds.

Coast Guard Station Miami occupies multibillion-dollar real estate across the channel from South Beach, but the atmosphere is different, destitute of cabanas and teepees. Coasties on the wharf awaited our lines. As the captain edged her sideways, harbor mud billowing outboard in the thruster wash, a salsa party aboard an awninged pontoon craft passed astern. Laughter, music, bottles clinking, dancing revelers in white suits and dresses, someone singing about his broken *corazon*—we were far from the ocean now.

"So are you willing to go out again?" Chris wondered, salsa fading.

"Sure."

"The next trip is in March. Same ship, only more crowded, and same study line, but this will be a different project. It's a collaboration between us and British oceanographers called RAPID/MOCHA to measure the MOC all the way across the North Atlantic."

"MOC?"

"The Meridional Overturning Circulation."

I had never heard of the Meridional Overturning Circulation at the time.

"Molly Baringer will be chief scientist. She'll be here tomorrow to help us pack up. I'll introduce you. She'll sign you on."

"Well, okay."