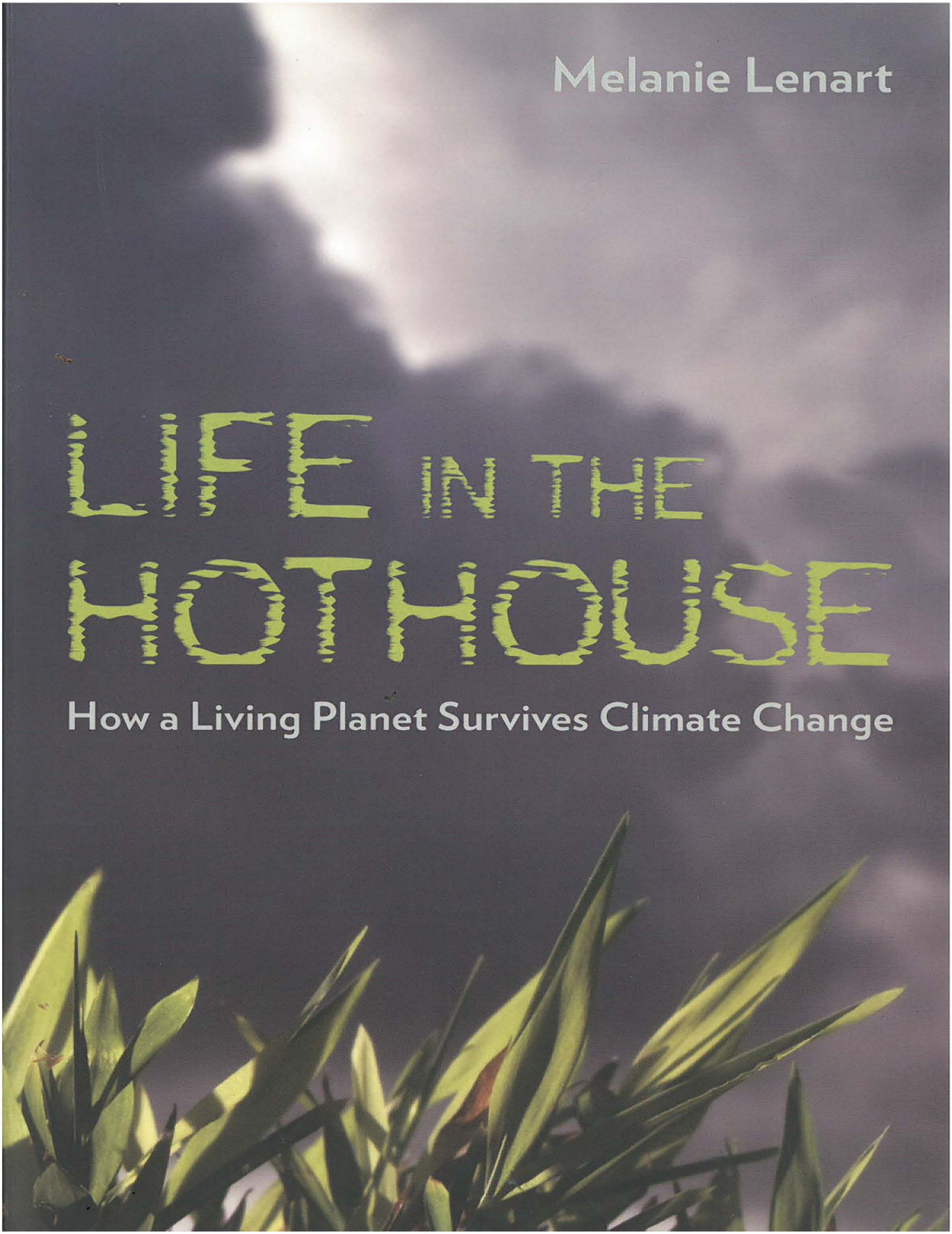

Melanie Lenart

LIFE IN THE HOTHOUSE

How a Living Planet Survives Climate Change

1

A Feverish Response

Hurricanes Come with High Temperatures

Huddling under an overturned couch while Hurricane Hugo raged over Puerto Rico, I wondered why on earth hurricanes existed. A native of Chicago, I had never experienced the shrieking winds and incessant rains that come with major hurricanes. Tornado warnings faded away within hours, and I had never landed in the path of these relatively skinny twisters. Hurricanes stretch across hundreds of miles with rains that can last for days. I hoped upending the couch would protect me from a potential ceiling collapse. Dozens of hours, millions of toppled trees, and billions of raindrops later, the storm had passed. The San Juan area fared surprisingly well, although things would have been different if floodgate glitches that occurred had led to the Carraizo Dam's collapse. If the dam had collapsed, tens of thousands of us might have been threatened by floodwaters, later reports revealed. Instead, the tropical rain forest on the island's northeastern end absorbed the brunt of the storm's force. This experience and the heartening revival of the tropical forest over the next few months impressed me. Hurricanes stayed on my radar throughout my subsequent studies of forests, rivers, and global climate change.

It may make sense for a warming world to produce stronger hurricanes as temperatures rise, somewhat as people might sweat on a hot day. Greenhouse-gas emissions by society have been heating things up, so it's logical to expect Gaia to respond with efforts to maintain climatic equilibrium. To reiterate, Gaia theory holds that over the long term, our living Earth—Gaia—has ways of keeping its climate within a range suitable for life. Could hurricanes play a role in tweaking the planetary thermostat? Unfortunately for those of us who end up in their paths, my subsequent research and conversations with experts indicate that this cooling function helps explain their existence. Exploring some of the reasons for this claim can offer an introduction to one way of viewing planetary dynamics through a Gaian filter. This particular Gaian perspective adds an element of reverse engineering—that is, an attempt to work backward from planetary responses to possible values for those responses.

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Hurricanes have a regulatory reason to exist when it comes to planetary cooling, for both physical and biological reasons. Let's start with the physical, always a good idea when considering planetary health. Although hurricanes may look like a way for a vengeful planet to let off steam, they actually cool the sweltering tropics by redistributing heat to other regions. This cooling function helps explain their existence. Hurricanes arise in the tropics, generally between 6 degrees and 20 degrees from the equator. (Closer to the equator than 6 degrees, the Earth's rotation doesn't impart enough spin to bring them into circulation.) After they mature, they're more able to withstand the cooler seas and stronger wind shear outside of tropical latitudes. By definition, the tropics receive a direct blast of sunlight at some point in the year. These spot-on rays contain more energy per square foot at Earth's surface than the angled rays reaching areas where the globe curves more blatantly. Consider a flashlight beam: If you aim it directly at a spot on the wall, it shines brightly on a small area. If you angle it to cover more ground, a weaker beam sheds light on a larger area. The tropics receive direct beams, some of them several times stronger per square foot than those striking Canada. This focused energy warms seas, makes clouds, and spawns hurricanes. All of these processes use heat.

The tropics are net exporters of heat, sending it off via winds, ocean currents, rain—and, of course, hurricanes, which employ all three methods of shifting heat elsewhere. It takes a lot of energy to warm water and to turn it into vapor, energy that could otherwise heat the air. Wind and heat often carry this captive energy up and away, until it escapes from its bonds when water vapor condenses into raindrops or snowflakes. Likewise, hurricanes cool the air by converting rising heat into the kinetic motion of swirling winds. Hurricanes also push heat downward and poleward as they surf the waves. Through basic physics and its interactions with its environment, hurricanes serve to cool the tropics. It's only logical, then, to expect a warmer world to feature more intense hurricanes.

Planetary mechanisms seem to support this logic. It's no coincidence that hurricane season typically starts as summer peaks and fades away by the winter solstice. High temperatures at the ocean's surface kick hurricanes into action. Other rules apply, too, especially in the hurricane's formative stage. High-level winds must be calm enough not to shear off the storm's head of steam. Hurricanes also need a lot of humidity. The humidity issue helps explain why dusty air can suppress hurricanes, as it may have done during the unexpectedly mild 2006 Atlantic season. Once an intense hurricane is off and spinning, though, sea-surface temperature seems to drive or at least predict its power surges, as hurricane expert Kerry Emanuel of the Massachusetts Institute of Technology has found. When explaining a hurricane's intensity, Emanuel found no need to invoke wind shear or any of the other factors affecting hurricane formation. Knowing the ocean temperatures around the hurricane eye gave him enough information to mathematically mimic most of the ups and downs of several intense hurricanes he modeled in a 1999 *Nature* paper.

Surface waters must reach about 80 degrees Fahrenheit to get these storms rolling. Waters topping 83 degrees seem to bring on more intense Atlantic hurricane seasons. This general pattern also comes through at the scale of individual storms encountering warm waters. That's not to say that every hurricane strengthens when it hits warm water. Other factors do come into play, most notably wind shear. But there's little chance a hurricane will attain major league status without passing over warm water.

Even hitting a pocket of warm water can amplify hurricane winds, if atmospheric conditions don't interfere. That's what Lynn "Nick" Shay of the University of Miami and others reported in a 2000 *Monthly Weather Review* paper describing their findings on the Gulf of Mexico's 1995 Hurricane Opal. This storm leapt from Category 1 into Category 4 in just fourteen hours while crossing a roaming pocket of deep warm water. In 2005, Shay and some of his colleagues flew right over Hurricane Rita to test the waters in the Gulf of Mexico. Winging into the eye of the storm, they dropped measuring devices into the churning depths. Their sea-tossed thermometers continued reporting temperatures as they sunk, to depths as low as 5,000 feet. With these efforts and others, they documented that 2005 Category 5 Hurricanes Katrina, Rita, and Wilma intensified while passing over warm waters related to the Loop Current—a tongue of deep, warm water lapping into the Gulf from the Caribbean. "All three of those storms interacted with the warm current—the Gulf of Mexico Loop Current—and all three of them exploded," Shay said. "You can actually think of these deep warm pools as fuel injectors."

Swimmers know that surface waters generally run the warmest, whether it's an ocean or a lake or even a pool. The deeper the warmth penetrates, the more potential it has to rev up hurricanes. Although hurricanes don't create whirlpools, their winds thoroughly stir up the ocean beneath them. They also displace water, pushing it ahead as a formidable storm surge. "Even out in front of the storm, the winds are already mixing the oceans," Shay noted. "By the time the eye of the storm is close by, it's really feeling the mixed layer temperature."

A shallow layer of warmth on a deep, cool sea soon turns into a lukewarm mix, with little energy to power hurricanes. This helps explain why eastern Pacific hurricanes often drop down to tropical storm status if they head north. The Pacific region off Baja California actually launches more hurricanes than the coast of Africa, the birthplace of many Atlantic hurricanes, but these eastern Pacific hurricanes get cold feet if they head north. A frigid current from Alaska soon cuts off their charge. (Of course, that current could warm as Alaska's temperatures continue to rise.) In contrast, Atlantic hurricanes can ride the Gulf current to reach as far north as Canada, though rarely with an intact eye and the extra punch that comes with it.

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There's a flip side to this churning action of hurricanes that hints at a Gaian role. When hurricane winds mix the ocean, they leave a trail of cooler waters in their wake. That's what atmospheric scientist Morris Bender and oceanographer Isaac Ginis documented in a 2000 paper. Hurricanes tangibly cool the sea surface around them through evaporative cooling and by mixing in cooler waters from depths where the sun doesn't reach. A hurricane's influence on the ocean beneath it easily extends down 300 feet, and up to 1,000 feet in some cases. Meanwhile, the sun's rays typically penetrate about 300 feet at best. (Of course, warm currents like the Gulf Stream can provide another source of heat.) In a computer animation of Katrina's path that Bender and Ginis posted on the Geophysical Fluid Dynamics Laboratory's Web site, the sea in front of Katrina shows up in blazing red, with surface temperatures registering in the mid-80s in degrees Fahrenheit. Behind the storm, temperatures fade to a cool blue, registering in the mid-70s and below. This surface cooling can last a week or more, potentially affecting future storms, Ginis noted. For instance, when Hurricane Danielle in 2004 crossed the same path used by Hurricane Bonnie four days earlier, Danielle's winds dropped from about 80 miles per hour to 65 miles per hour.

Bender, Ginis, and another colleague compared more than a dozen hurricanes and found that their ability to cool the surrounding sea related directly to the time they lingered over an area. Loitering hurricanes cooled the surface by an average of 10 degrees Fahrenheit, whereas fast-moving hurricanes cooled it by about 3 degrees Fahrenheit. Hurricane Georges dawdled in the Gulf of Mexico long enough to cool sea-surface temperatures by up to 6 to 9 degrees Fahrenheit in its wake, making its path to the southern coast (including Louisiana) visible for weeks using temperature-detecting satellites. Thanks to satellites that can sense infrared heat, it's easy to see that hurricanes cool the ocean surface along their paths.

Can hurricanes effectively cool the sea surface from one year to the next? Maybe this would help explain why the 2006 Atlantic hurricane season thankfully fizzled out almost before it started. The 2005 Atlantic season produced twenty-eight named tropical storms, a high in the more than fifty years of reliable records. The 2004 season was no slacker, either, yielding fifteen named storms, including a record four hurricanes striking Florida in one season. In contrast, only five named Atlantic storms formed in the 2006 season. Other factors also intervened, including an El Niño event. In a 2007 *Scientific American* article, climatologist Kevin Trenberth linked the relatively mild hurricane season to stronger wind shear during a 2006 El Niño event as well as cooler sea-surface temperatures that season, which he related to heavy trade winds during the preceding winter. Theoretically, the previous hurricanes also could have contributed to cooler seas in 2006. Perhaps the 2004 and 2005 Atlantic hurricanes helped export enough heat from the tropical Atlantic to prevent another catastrophic hurricane season on their heels.

This idea is speculative, but not without support. A 2007 analysis by Ryan Sriver and Matthew Huber of Purdue University indicates that hurricanes acted to cool the surface of many cyclone-prone seas during the period they considered, between 1982 and 2001. They found a pronounced cooling in the Gulf of Mexico and the Atlantic from the Caribbean north up the U.S. East Coast to Canada. Much of Asia's east coast also registered extensive cooling, as did Southern Hemisphere pockets favored by hurricanes. This cooling occurred even as the world's oceans warmed overall along with the planet as a whole. Estimating the surface cooling to 150 feet deep in hurricane-prone regions, Sriver and Huber figured hurricanes could account for about 15 percent of the heat moving out of these regions in a typical year. Huber, an associate professor at Purdue who often works from a laptop in the local Café Vienna, explained by e-mail that the climate-change community has expressed strong interest in his research, but most oceanographers still resist the concept that short-lived storms could redistribute so much heat. "No one has thrown tomatoes yet, so that's good, but I think the community is still skeptical, which is fine," he added.

Still, scientists have long recognized that some line items are missing in the tropical heat budget. The current numbers do not account for all the heat known to move from the tropics to the subtropics. Meanwhile, Sriver and Huber's research shows that the more intense storms move the most heat. As Huber put it, "Strong storms lead to more ocean mixing than weak storms that last longer." A 2008 paper of theirs with colleague Jesse Nusbaumer, based on higher-resolution information from the tropics for the 1998–2005 period, suggests the amount of surface cooling occurring could be even about a third higher than their earlier estimates. In response to my question about whether the hurricane-cooled surface might help explain the relatively mild 2006 Atlantic hurricane season, Huber responded: "I think that's possible, but by no means proven. It's conceivable that a huge amount of heat was flushed downwards (and cold mixed up), but we may see that heat back again." Emanuel's work, some of which is described in a 2001 paper, suggests that most of the heat is lurking in deeper waters poleward of its tropical source.

Even while cooling the tropical oceans with their winds, hurricanes also cool the tropical air and sea by promoting evaporative cooling and by exporting rain. In fact, rainfall processes associated with hurricanes moved about three times more heat out of the tropics than ocean cooling, estimated Kevin Trenberth and John Fasullo in a 2008 paper. Hurricanes will pull in air moisture from up to 1,000 miles away. All the rainfall that comes down in days-long downpours or drizzles started out as water somewhere on the surface. And the evaporation of water lifts heat from a surface—whether skin, land, or sea. The thunderstorms that shape hurricanes, forming arms of convective clouds that stretch far from the hurricane's eye, arise specifically because of heating at Earth's surface. The heat transforms into another form of energy, in this case the energy that turns earthbound water into airborne gas. (Remember, old energy never dies, it just changes form.) At some point, that gaseous water vapor will reach a point where it can no longer sustain its free-floating lifestyle. Often, that moment occurs after it has departed the warm confines of the tropics. When it heads back down to earth, it releases the energy it collected to fuel its journey. Similarly, hurricanes themselves wind down at some point, especially after departing the energizing tropics. The winds and rain they carried with them share energy and heat with distant lands. But in their tropical stomping grounds, and anywhere they use latent heat from evaporation to fuel their powerful winds, hurricanes are helping to counteract the buildup of heat that comes with global warming.

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Hurricanes evolved as a cooling mechanism long before people built cities in their paths. Even so, it's easy to take a hurricane personally in the heat of the action. Raging winds, crashing trees, roaring rivers—even the descriptions of what happens inside a hurricane bring to mind an angry god or goddess. Perhaps it is the god Hurakán, a pre-Columbian deity of the Tainos, the Caribbean islanders who passed down the western word for these winds of destruction. Or maybe Kali, the Hindu goddess of destruction with her many arms. In most of Asia, these swirling storms are called typhoons, which some relate to the Cantonese phrase *tái fung* (great wind). By any name, tropical cyclones are all the same at the core: low-pressure systems surrounded by high-speed winds swirling around an inner circle, with multiple stretches of thunderstorm clouds circulating in the outer reaches. And they're big, typically stretching hundreds of miles across. Tropical cyclones that sustain wind speeds of 74 miles per hour or more qualify for hurricane or typhoon status based on the commonly used Saffir-Simpson hurricane intensity scale. In this book, I'll use "hurricane" to describe all tropical cyclones that cross this wind-speed threshold. It seems fitting to follow the Taino tradition, as I experienced two major hurricanes on the Caribbean island the Tainos called Boricua.

My second encounter came about a week after I returned to this enchanting Caribbean island, now known as Puerto Rico (although to this day, islanders often refer to themselves as Boricuas). Following a two-year stint at graduate school, I had come back in September 1998 to collect information on uprooted trees for my dissertation. A few days after my arrival, word got around that an Atlantic storm was headed in our direction: Hurricane Georges (pronounced "zhorzh"), presumably named in honor of French-speaking Caribbean islanders. Visions of uprooted trees ripe for the measuring made me perhaps one of the only islanders with positive thoughts about the coming event. Somewhere inside of me, a scientist rubbed her hands together in anticipation. I was yanked back to the reality of being human by some news that arrived with my breakfast on the morning before the hurricane's projected landing. Georges's sustained winds had reached 150 miles per hour. Another 6 miles per hour would push it into Category 5 status—the highest ranking on the Saffir-Simpson scale of destructive power. Fear thudded into my stomach, destroying my taste for scrambled eggs. There was no turning back now. It's impossible to evacuate an island of nearly 4 million people, even with several days' notice. So we boarded up windows, stocked up on canned soup, batteries, and beer, and waited. At least this time I would share the experience with friends in the forest instead of alone in an urban rental, where I had spent much of Hurricane Hugo when it roared past San Juan.

While the electricity lasted, we watched the satellite images of this Texas-sized cyclops navigating the Atlantic at 20 miles per hour—the typical slow-motion lurch of hurricanes. Georges stretched several times the size of Puerto Rico's 100-mile length. At times, the eye diameter alone matched the island's 35-mile width. That's bad news. Although people use "eye of the storm" to describe the relatively cloud-free and calm center, the eyewall circling it marks the most ferocious winds of the beast. Luckily, before Georges cast its eye upon Puerto Rico, its sustained wind speeds dropped to about 115 miles per hour, placing it into a more manageable Category 3. My friends and I spent some of the night reinforcing a wall of their wooden home in the mountains outside of Luquillo, near the hurricane's point of entry on the island's eastern end. But we remained safely sheltered throughout the storm.

During the eye's eighteen-hour passage across the length of Puerto Rico, Georges blew off roofs, uprooted trees, launched landslides, and flooded cities. Two days of rainfall totaling 28 inches devastated the mountain town of Jayuya. Four out of five of the wooden structures crumbled on the associated islands of Vieques and Culebra. Some 73,000 homes in Puerto Rico were destroyed or damaged, like a cliffside home we drove by that was filled with mud from a landslide. Although no one in Puerto Rico died directly from the hurricane, several died in the aftermath. In the Luquillo Mountains, we drew our electricity from noisy generators for about a month and washed in the nearby Sabana River while local teenagers treated the powerless wires overhead as jungle-gym equipment. Sudden surges of electricity into these dormant cables caused a few deaths around the island in the weeks after the storm. Still, by the time I left Puerto Rico nearly four months later, life had returned to a semblance of normality. Traffic moved in its usual erratic patterns, splintered forests sported a new set of greenery, and carpenters labored to repair the damaged structures. People went about their business.

In contrast, vast expanses of New Orleans still looked like ghost towns four months after the August 2005 strike from the more intense Hurricane Katrina. A weeklong stay in December of that year to document the impacts and lend a hand in relief efforts put me amid the lingering devastation. Piles of furniture and debris lined the sidewalks in front of homes that had been soaked by floods. Blue tarps flagged damaged roofs throughout the city. Knee-high signs sprouted around traffic stops advertising home-gutting services, lawyers, and toll-free numbers to call for quick home sales. In the Lower 9th Ward, most commercial and residential streets looked deserted, with the occasional family arriving for days or weeks to check damages and consider whether to attempt repairs.

It was easy to see why so many structures remained abandoned despite the typical façade of normalcy on the outside. The exterior mud lines from the waist-high floodwaters had faded away, but the inundation had allowed toxic black mold to insinuate itself into the interior woodwork and walls, along with a host of other lung-damaging substances. Survivors had a name for the trouble with breathing the local indoor air: the Katrina Cough. All these flooded homes required gutting, a dangerous task even with the respirators and space-age suits worn by the brave souls who ventured inside. During my brief stint with the relief group Common Ground, these courageous volunteers included more than a hundred people willing to gut houses by day and sleep fifty to a room by night in the Baptist church the group was in the process of restoring at Pauline Street and Claiborne Avenue.

Down the street from the Common Ground distribution center, I met Kirk Armelin, who agreed to tell me his story. “This is the house I was raised in since ’66 or ’67,” Armelin said, gesturing back to a pink bungalow that maintained its exterior charm. “We get hurricanes like they get blizzards up north. I’ve been through Betsy, Camille—none of them never did nothing. The furthest the water’s ever been is the third step right here,” he said, pointing with a broom to a step about a foot off the ground. “But this one took a toll. This one took everything.” Like many in the neighborhood, his house filled halfway up with a toxic stew of muddy water during Katrina. Versions of Armelin’s story could be repeated 150,000 times over in the city known as the Big Easy. That was the rough tally for the number of Katrina-damaged homes in the New Orleans area alone.

Right next to the 9th Ward, the French Quarter's higher ground and stucco construction helped its ancient buildings endure several centuries' worth of major hurricanes, including Katrina. Still, problems arose in this eighteenth-century neighborhood from the wind, lack of electrical power, and lawlessness that prevailed for days and weeks following the hurricane. The power outages did their own damage, as I learned from Market Café owner John Tsatsoulis. Four months after Katrina hit, Tsatsoulis was still struggling to get his French Quarter business reopened. The day I met him, he was having new commercial refrigerators and freezers installed to replace the ones destroyed when rotting food formed acid leachate during the power outage. While we sat at the empty circular bar with its expansive view of Decatur Street, Tsatsoulis sadly showed me pictures of what used to be his home in Lakeview, the neighborhood bordering Lake Pontchartrain. A storm surge on top of rains had overpowered the 17th Street Canal and the resulting breach inundated many homes in this formerly ritzy neighborhood. In the Tsatsoulis residence, water rose past the gutters, weakening the structure enough to pull down the ceiling. After we looked at the images of his former home as a pile of debris, he shook my hand warmly and said he appreciated research on how these problems relate to global warming.

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Atlantic hurricane damage and high temperatures went hand in hand in both 1998 and 2005, the world's two hottest years in the instrumental records (at least as of publication). This does not prove anything. It could well be coincidence. Still, rising sea-surface temperatures relate to both. Warm oceans helped push 1998 into the record books as the world's hottest year in at least a century—and possibly in a millennium, when instrumental records are compared to records developed from tree rings and other natural archives. The year 1998 also made the record books for highest insured losses from weather-related events around the world, estimated at $92 billion. About a month after Hurricane Georges menaced Puerto Rico and the Gulf Coast, the even more powerful Hurricane Mitch crossed the Atlantic to reach Central America. High sea-surface temperatures accelerated wind speeds of both Georges and Mitch. Damage tallies cannot begin to account for the cost of the storms. Mitch killed about 11,000 people when it plowed through Honduras, Nicaragua, El Salvador, Guatemala, and Belize. After passing over a section of warm ocean current, Hurricane Mitch's sustained winds reached an estimated 180 miles per hour out at sea. It dropped to about 150 miles per hour—just below the Category 5 threshold—right before its eye breached land in Honduras. Of course, half the storm preceded the eye, and Emanuel's work has shown that conditions right around the eyewall matter most to hurricane dynamics.

Less than a decade later, 2005 challenged 1998 as the warmest year in the instrumental record. Different analytical approaches yield different results for which year was hotter, but they were both scorchers. And 2005 brought the Atlantic three Category 5 storms, featuring Hurricanes Rita and Wilma as well as Katrina. The 2005 hurricanes went on to break U.S. records for insured costs as well, according to the National Hurricane Center's report on Katrina. The cost in lives was high as well. More than 1,300 people died throughout the South, with at least 1,000 from Louisiana, more than 200 in Mississippi, and the rest in Florida, Georgia, and Alabama. A shamefully deficient emergency response made things worse. But there's no question that the risks and challenges become much greater as hurricanes gain power.

The difference in destructive power among hurricanes is tough to capture with the Saffir-Simpson five-category scale. In reality, the categories make near-quantum leaps in ferocity. On my December 2005 flight from Colorado to New Orleans via Memphis, I sat next to a fourteen-year-old girl, Mary Katherine, who recalled playing in the waves among surfers when the Category 2 Hurricane Dennis passed near Jamaica while she and her family were vacationing there earlier that year. You might think Dennis's 50-mile-per-hour winds would carry about one-third of the destructive power of Mitch's 150-mile-per-hour winds. But no. With the exponential difference factored in, Mitch contained roughly *twenty-seven times* the destructive power of Dennis, with tragic results. Hurricane Katrina's destructive power fell closer to Mitch's than Dennis's on the spectrum. The 134-mile-per-hour gusts measured in Poplarville, Mississippi, during Katrina delivered nearly twenty times the destructive force of Dennis's winds. Katrina also heaved in a wall of water to flatten many homes in Gulfport, Mississippi, where Mary Katherine lived. She and her family were headed home to rebuild their lives after visiting relatives in Colorado. "At least we got away from the destruction for Christmas," the lanky brunette said with a philosophical shrug.

When Katrina's eye breached land at Buras, Lousiana, its sustained winds of about 126 miles per hour fell just under the 131-mile-per-hour speeds required to qualify for a Category 4 storm. But because a hurricane's destructive power increases exponentially with wind speeds, Katrina contained about twice the destructive power of Hugo's 92-mile-per-hour winds in San Juan, even though both qualified for Category 3 status. (Hugo qualified because its winds were stronger around the eye, which crossed over the island's northeastern corner.) While Hugo's 1989 efforts to burst through the island's Carraizo Dam floodgates failed—just barely—Katrina's extra punch gave it a final surge of power that tipped the scales: Its floodwaters broke through several crucial levees just when residents were beginning to hope that the worst of the storm had passed. This led to destruction so widespread it remains to be seen whether parts of this beloved Louisiana city will ever recover, especially in "the bowl," as locals call the dip in the land so clearly delineated in the flooding that followed in Katrina's wake. This is the area where so many of the city's people lost their lives—linked in part to an emergency response that was widely acknowledged to have been a disaster in its own right.

Many Katrina survivors said their insurance companies were refusing to pay for flood damage even though they had hurricane coverage. News reports concurred with their impressions, suggesting insurance would cover only half or less of the estimated $100 billion in damages. Yet, from a scientific perspective, floods fall squarely within the realm of hurricane destruction. Hurricane category generally predicts the heights of accompanying storm surges. For instance, Katrina pushed a wall of seawater onshore that reached 27 feet high at Hancock, Mississippi, and stretched inland for 6 miles—as befitting the Category 5 status it held a mere twelve hours before its eye reached land. Most of the people killed by Katrina died in floods. Similarly, most of the deaths from Hurricane Mitch's 1998 rampage through Central America resulted from floods and related landslides. The mountainous terrain that helped break up Mitch's eye and slow wind speeds also prodded the storm into unleashing torrents of rainfall. An estimated 50 to 75 inches fell on some towns, washing out hillsides and damaging millions of homes. Flash floods and mudslides also killed most of the 600 people who died in Hurricane Georges, mainly in the Dominican Republic and Haiti. In fact, floods, rather than winds, have caused most hurricane deaths documented over the past few decades.

Heavier rains come with stronger hurricanes, as Arizona State University geographers Randall Cerveny and Lynn Newman found when they compared nearly 900 tropical cyclones using satellite imagery. Every 22-mile-per-hour increase in sustained wind speeds brought an extra inch of daily rain on average, based on their analysis. Given the documented tendency for hurricane rains to increase with winds, climate modelers Thomas Knutson and Robert Tuleya estimated that hurricane rainfall would increase by about 18 percent by mid-century given the projected warming of tropical oceans. Rainfall tends to come in more intense storms in a warmer climate (as chapter 4 will describe). That doesn't mean every extra hot year will bring more hurricanes and floods. It does mean the odds of stronger hurricanes accompanied by bigger floods are going up along with sea-surface temperature. As Robert Corell, chairman of the Arctic Impact Assessment, put it during a keynote talk at a 2006 Tribal Lands and Climate conference in Arizona, "Katrina is consistent with the fact that we will have more Category 4 and 5 hurricanes. As the planet warms—it doesn't take much warming—the volatility of the system increases."

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Warmer seas already are wielding stronger hurricanes around the world, as Peter Webster of the Georgia Institute of Technology and some colleagues reported in 2005. The team of four scientists estimated changes in hurricane strength using records from satellite imagery going back to the mid-1970s. These records cover the oceans and other locations lacking wind-measuring devices. The research team found an astounding jump in "intense" hurricanes—those with sustained wind speeds over 130 miles per hour—when comparing the first half of the satellite record with the second half. A full 269 intense hurricanes thrived during the fifteen-year period that ended in 2004, a 57 percent increase over the previous fifteen-year period. The difference averages out globally to an extra six intense hurricanes a year. Meanwhile, minor hurricanes had declined in number. The typical 80 to 90 hurricanes were still forming each year as before, but during the warmer period, more of them reached "intense" status. The satellite data remain controversial to some researchers, as do other less comprehensive records. Based on existing data, which are imperfect but available, a 2006 study by Ryan Sriver and Matthew Huber reached similar conclusions for individual ocean basins included in the analysis.

Also in 2005, mere weeks before Katrina struck, Kerry Emanuel had published similar results for the Atlantic and North Pacific—something he said surprised even him. Using observational records from 1949, he found that Atlantic hurricanes had nearly doubled in power since about the mid-1970s. As forecasters often do, Emanuel combined storm length and intensity into a value reflecting total destructive power of regional tropical storms (including hurricanes) for each season. Power rose and fell with average sea-surface temperature, both seasonally and across the decades. Since his findings were published in 2005, the distinguished Massachusetts Institute of Technology professor has been sounding the alarm about how global warming is strengthening hurricanes. Atlantic hurricane activity seems particularly in tune with sea-surface temperatures, more so than hurricanes in some other ocean basins, as indicated in his 2008 journal article written with colleagues. In 2006, Emanuel and lead author Michael Mann published an *Eos* article showing that Atlantic ocean temperatures tend to move up and down in sync with air temperatures in the Northern Hemisphere, at least when averaged by a decade at a time. The results imply that as long as greenhouse gases continue to heat up the Northern Hemisphere, the Atlantic will continue to spawn intense hurricanes.

Critics of the theory that greenhouse gases are involved in warming the hurricane-prone Atlantic argue that natural variability of the ocean currents might explain the jump in hurricane power, and they question whether the observed increase is real or merely a result of improved detection in recent decades. Those favoring natural variability and improved detection include respected National Hurricane Center researchers William Gray and Christopher Landsea. In 2009, Landsea was the lead author of a *Journal of Climate* paper touted as showing that the observed increase in the number of tropical storms and hurricanes in the past century related to improved detection. The authors concluded that a perceived increase in the number of "short-lived storms"—that is, those lasting two days or less—related to improvements in scientists' ability to detect these storms with modern technology. A co-author on that paper, however, pointed out in an August 11, 2009, press release issued by the National Oceanic and Atmospheric Administration that the study did not consider whether Atlantic hurricanes had strengthened in recent times. As co-author Thomas Knutson noted, the study "does not address how the strength and number of the strongest hurricanes have changed or may change due to global warming."

As far as variability goes, all climate researchers recognize the challenges of distinguishing between an upward trend and a natural fluctuation from a thirty-year or even a fifty-year record. Like any climate pattern, hurricane intensity also waxes and wanes as part of natural climate variability. Collective hurricane power varies by year and even in fluctuations stretching across decades. In fact, Gray and Landsea were among those expecting an eventual rise in Atlantic hurricane power in the 1990s based on decades-long fluctuations of regional sea-surface temperatures and other factors. When it comes to natural variability, though, Atlantic hurricane activity tends to increase while activity decreases in other regions, most notably the eastern North Pacific. In contrast, the satellite-based analysis by Webster and his colleagues showed all six ocean basins registering an upswing in the number of intense hurricanes since 1990. What's more, the timing of the upswing echoed a documented rise in sea-surface temperatures of the same ocean basins—a rise linked to global warming from burning gas, coal, oil, and forests.

Gray maintains that a recent increase in Atlantic hurricane destructive power relates to natural variability rather than global warming. Perhaps this isn't surprising—he doesn't believe that society's emissions of greenhouse gases are warming the planet, as Chris Mooney describes in detail in his 2007 book *Storm World*. Still, decades ago, Gray identified sea-surface temperatures over 80 degrees Fahrenheit as one of the key ingredients in nature's recipe for hurricane formation. Sea-surface temperatures fluctuate based on factors besides global warming, too, of course. They move up and down with the comings and goings of ocean currents, from natural variability, and even from exposure to major hurricanes themselves, as described above.

Another major factor affecting a storm's ability to attain and retain major hurricane status involves vertical wind shear—the ability of high-level winds to bend hurricanes out of shape. As Landsea has noted, some computer models project that increased wind shear might largely offset the effect of warming seas. For instance, Gabriel Vecchi and Brian Soden compared eighteen global climate models and found that many projected an overall increase in wind shear over the tropical Atlantic and eastern Pacific. On the other hand, Landsea and Gray, writing with lead author Stanley Goldenberg and another colleague, reported a connection between above-average Atlantic sea-surface temperatures and below-average wind shear in a 2001 paper. A 2008 research effort led by Chunzai Wang similarly found that wind shear tended to drop when warm seas—in this case, those with temperatures above 83 degrees Fahrenheit—expanded their coverage of the tropical Atlantic.

Kerry Emanuel has been making the case for the link between rising air temperatures and rising sea-surface temperatures, but he, too, is quick to acknowledge that sea-surface temperature is only one of many factors affecting hurricane intensity. Over lunch in 2006 at the Tropical Cyclones and Climate workshop in Palisades, New York, Emanuel made a point of explaining to me that the rise in hurricanes' potential intensity with sea-surface temperature occurs in part because both have links to other factors. High winds cool the sea, and they often nip would-be hurricanes in the bud. Slower seasonal winds allow hurricanes to gather steam and also allow the surface to retain more heat. Volcanic eruptions, too, generally cool seas even as they produce other conditions that can thwart hurricane formation. "Part of the increase we see since the early 1990s is there haven't been many volcanoes," Emanuel explained, noting that the eruptions of Mexico's El Chichon in 1982 and the Philippines' Mount Pinatubo in 1991 almost certainly helped lower the intensity of Atlantic hurricanes during the earlier period of the record he analyzed. Volcanic particles tend to block some of the sun from reaching Earth's surface, which helps keep the sea surface cooler. Partly as a result, these particles tend to raise the temperature where they reside, in the upper troposphere. In contrast, hurricanes tend to be particularly powerful when a cooler upper troposphere sits above a warm surface—a common situation in recent years. "This is a big player, with what we've seen," Emanuel said.

Like any climatic factor, sea-surface temperature and other factors affecting hurricane formation sway in tune to natural variability as well as the longer-term influence of global warming. Still, even those who don't believe in the connection between global warming and stronger hurricanes have cause for concern based on the records of the past gathered by Kam-Biu Liu of Louisiana State University. He has looked at sediment cores from coastal lakes to tally dune-topping storm surges. "Each record would give us a sand layer, or fingerprint if you will, of a past storm event," he said during the 2006 Tropical Cyclones and Climate workshop. He has found a hyperactive period of storm activity stretching from about 3,800 to 1,000 years ago based on four cores from four different U.S. coastal states. Based on Liu's findings, even the past thousand years have been relatively mild. "We really haven't seen anything yet. What we've seen in the past, we may see in the future," he commented. After describing his work for U.S. coastal areas as well as some coastal regions of China, he urged caution when considering how future hurricanes might strike. “If the officials are basing their assessments on the last 150 years, then they are missing the boat,” he said. “And they may also be putting a lot of lives at risk.”

Liu’s concern received support from a later study of coastal lake sediments linked to landfalling Atlantic hurricanes, described in a 2009 *Nature* paper by Michael Mann and colleagues. They compared these overwash sediments for the past 1,500 years collected from sites in New England, the mid-Atlantic, the southeastern U.S. coast, the Gulf Coast, and the Caribbean. Their results showed that the frequency of these dune-topping storm surges peaked in medieval times (especially from about 1000 to 1200), then subsequently dropped to lower levels of activity for about five centuries (from about 1250 to 1750). Their independent comparison using computer modeling of other data suggested that during the peak, tropical Atlantic sea-surface temperatures were running high, even as the atmosphere favored a climate pattern that promotes lower wind shear in the Atlantic (that is, La Niña-like conditions in the Pacific Ocean). During the subsequent hurricane lull, their model suggested that these two situations reversed, with lower sea-surface temperatures and conditions ripe for higher wind shear. While the authors don’t highlight this fact, the peak they found occurred during the time frame known as the Medieval Warm Period. Meanwhile, the decline extended across much of the time frame encompassing the so-called Little Ice Age.

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Limited evidence suggests that hurricanes weakened as well during the last full-blown ice age and strengthened beyond anything we’ve seen yet during hothouse climates. First a caveat: It’s difficult to assess global hurricane activity during past climates. Sediments can reveal information about particular regions. Researcher Kam-Biu Liu of Louisiana State University and others have used sediments to begin piecing together some evidence for hurricane activity in specific coastal areas in the United States and China. But these records extend back only a few thousand years—an admirable accomplishment, but falling short by a long shot of the termination of the last ice age roughly 10,000 years ago. Also, hurricanes may strengthen in some regions while weakening in others, making a global assessment out of reach without a vast increase in research covering more space and time. For the moment, at least, researchers have to resort to computer models to consider how hurricane regimes might have differed in the past.

Jay Hobgood and Randall Cerveny tuned a global climate model to conditions of the coldest depths of the past ice age to see how hurricanes might fare. They concluded in a 1988 paper that these storms could still operate in this glacial climate, but in a weaker state than during interglacial warm periods, including the current climate. In our modern climate, hurricanes won't form unless tropical sea-surface temperatures reach about 80 degrees Fahrenheit. The threshold temperature for hurricane formation would have dropped slightly in the ice-age atmosphere, just as it is likely to rise somewhat in warmer times. Even taking these changes into consideration, hurricane intensity likely would decline in ice-age climates, these researchers concluded.

The situation would reverse in hothouse climates. In fact, the evolving understanding of how hurricanes function under different climates might help explain a long-standing puzzle about earlier hothouse worlds. Oceanographers and climatologists have struggled to explain two irreconcilable "facts" about earlier hothouses such as the Eocene and Cretaceous—one, a warmer global climate, with little or no permanent ice even at the poles, and two, tropical seas that would have made surfers reach for their cold-water gear. How could sea-surface temperatures bordering the equator run between 59 and 73 degrees Fahrenheit, as the oxygen isotope evidence suggested, when palm trees were swaying at the latitude of modern-day Chicago? This "cool tropics paradox" caused climatologists to scratch their heads and computer models to sputter. Climate models needed tropical sea-surface temperatures above 86 degrees Fahrenheit in order to reproduce the warm polar Eocene climates that came out loud and clear in the fossil evidence of the animals and plants that lived at these high latitudes.

In the past decade, evidence arrived from several fronts to challenge the illogical results showing that ancient hothouses featured cool tropical seas. Paul Pearson of Cardiff University and colleagues suspected that the material used in earlier research had been too old and crusty to provide reliable dates. Sitting on the cold ocean floor for 50 million years (Eocene) or 100 million years (Cretaceous) might alter the information locked in the shells, they reasoned. So they sought out pristine samples from materials that had retained their shape and glassy look after all those years, tossing out any specimens that had begun to blur around the edges. Results published in 2001 from these pristine samples showed that tropical sea-surface temperatures averaged between 82 and 90 degrees Fahrenheit during the late Cretaceous and Eocene hothouses. A follow-up effort in 2007 put the tropical sea-surface temperatures around Tanzania between 86 and 93 degrees Fahrenheit throughout the Eocene. The high end is several degrees hotter than is reached in the open ocean today and about the temperature we're starting to get in summer in some parts of the Gulf of Mexico and Caribbean Sea.

"It's a useful rule that the sea-surface temperature never exceeds 86 degrees Fahrenheit in the open ocean today—it only happens in isolated basins," Pearson explained in an e-mail exchange. "So, yes, the temperatures are looking quite toasty." Other researchers used a similar approach when reexamining tropical sea-surface temperatures during the hothouse Cretaceous. Karen Bice of the Woods Hole Oceanographic Institute headed a research effort to examine pristine material from the Cretaceous hothouse. Their results, published in 2006, suggested that sea-surface temperatures in the tropical Atlantic around Suriname reached 91 to 95 degrees Fahrenheit during much of the Cretaceous. Now that's getting warm—but perhaps still tolerable with a proper sea breeze.

Sea temperatures that high can spur on more than a sea breeze, of course. There is some evidence that high sea-surface temperatures during past hothouses provoked storms of an intensity far beyond what we've seen in the historic record—even beyond what sediments have recorded for the past several million years. In a creative approach, Japanese researchers used lines in the sand to compare storm intensities over the past quarter of a billion years. Makoto Ito and his colleagues at Japan's Chiba University measured the distance between wavelengths preserved in ancient sandstone that fit the profile of near-shore storm deposits—pockets of fine-grained sand of the sort pulled into the sea during hurricanes and other intense storms. These "tempestites," named after the tempests that create them, differ in appearance from the silty muds that settle to the seafloor in calmer times, sandwiching them in. The color and texture of tempestites often stand out, making visible the curvy imprint of the wave action they preserve in hummocks as sand begets sandstone. These hummocky formations originate from waves washing over the seafloor, rearranging sand into a series of raised bumps separated by slight depressions. Like washboard bumps on a dirt road, the bumps in hummocky tempestites tend to be evenly spaced. The "wavelength"—that is, the distance between the bumps—reflects the severity of the storm, based on analyses of modern tempestites. Basically, bigger waves yield bigger wavelengths.

Ito and colleagues measured the wavelengths of hundreds of storm deposits around Japanese islands, with samples dating from about 260 million years ago during the late Permian through a million years ago during the Quaternary. The Cretaceous, which stretched from 144 million to 65 million years ago, contained numerous samples. When they pulled their data and findings from similar studies together onto one timeline, published in 2001, they found that storm intensity peaked during the mid-Cretaceous—right about when global temperatures peaked in the half-billion-year record. The tempestites laid down during the mid-Cretaceous contained wavelengths about 20 feet apart, triple the distance of those formed by even the most severe modern storms.

Circumstantial evidence like this cannot prove causality. In this case, the researchers cannot even prove that hurricanes caused these formations, as they note. And the results do not reveal exactly how big those storms were, say, on the Saffir-Simpson scale of hurricane destructive power. Still, the concept that bigger storms would create greater wavelengths fits our understanding of how these formations work in modern times. And the greater wavelengths found during the hothouse Cretaceous supports our understanding that higher sea-surface temperatures can support more intense storms. It also supports the argument that we should do our best to avoid raising global temperatures high enough to bring the planet back to a hothouse state.

Factors that can dampen hurricane strength—such as wind shear, dusty skies, and cool ocean currents—may intervene along the way to keep wind speeds from escalating off the charts as the world warms. Even the hurricanes themselves help cool down the tropics. But we are entering uncharted territory on ocean temperatures, at the surface and below, so all projections contain elements of speculation. What we do know should give us cause for concern. We know hurricanes require warm sea-surface temperatures to get rolling and that warm waters at the ocean surface and below power their winds and rains. And we know global warming heats up the oceans, almost by definition. So coastal residents in particular and society in general better prepare for a continuing onslaught of strong hurricanes, typhoons, and tropical storms as long as we continue to warm the planet. Not only does the physical evidence show that these storms intensify as ocean temperatures rise, but Gaian logic suggests that there are good reasons for this reaction. So there is a silver lining to these cloudy skies. Hurricanes help Gaia survive and moderate global warming, even cooling tropical seas on a real-time basis. What's more, hurricanes can help cool things down via their effects in the biological realm.

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Hurricanes also seem to assist Gaia's efforts to beat the heat via plants, which draw down heat-trapping carbon dioxide. Research efforts by dozens of scientists point toward similar results: In both the forest and the sea, hurricanes boost productivity—meaning the hard work of plants as they build carbohydrates out of carbon dioxide, water, and sunlight. It's an important job, as atmospheric carbon dioxide shoulders the blame for about three-fifths of the modern global warming. By the start of this century, carbon dioxide levels were about a third higher than they were before the Industrial Revolution brought us cars, coal-powered electricity, and central heating. By the end of this century, levels could double or even quadruple preindustrial levels. Anything that helps pull carbon dioxide out of the air potentially helps slow global warming.

Plants pull carbon out of the air and add hydrogen from water molecules to construct carbohydrates—the building blocks of life. Carbohydrates form marine algae and forest leaves as well as longer-lived organic carbon structures, such as wood and soil organic matter. Hurricanes shift some of these constructs of carbon dioxide into potential deep storage when their floods carry leaves, wood, and soil organic matter into waterways, wetlands, and the sea. It may seem ironic that any living thing could benefit from this force of destruction called a hurricane. Maybe it's a matter of life celebrating its survival. More likely, it's life enjoying the boon of nutrients coming up from the seafloor, down to the forest floor, and from the river to the sea.

In the ocean, hurricanes boost the growth of marine plants, including algae and microscopic plankton. Like Robin Hood, a hurricane redistributes the wealth. It lifts valuable fertilizers from nutrient-rich deep waters and sediment deposits into the nutrient-poor surface waters where the masses live. In fact, the nutrient deficit at the sea surface specifically stems from the crowding of plant life into the top 300 feet. Known as the photic zone, it's the only place marine plants can catch some rays. In the churning wake of a hurricane, plankton and other plants bloom in numbers as they feast on nitrogen, phosphorus, and other micronutrients. Post-hurricane bursts of algal productivity show up in satellite images, under the eyes of those who know how to detect photosynthesizing chlorophyll. Researchers Amélie Davis and Xiao-Hai Yan found that chlorophyll levels typically doubled in the days after a hurricane's passage, based on their satellite-imagery study of seven storms passing over the northeastern U.S. continental shelf. Davis cautioned that the results should be taken with a grain of salt—or perhaps a grain of sand—because satellite imagery can confuse algae with sediment. Still, in one remarkable example, the Category 5 Hurricane Isabel produced a 340-mile-long strand of algae that drifted around the coastal area for two weeks before disappearing from their radar as it joined the food chain or sank toward the ocean floor.

Admittedly, algal blooms are not the most desirable forms of life. Some might call them the scum of the earth. But at the microscopic level, they're just another host for chloroplasts, a member of the bacteria group that Gaia theory co-developer Lynn Margulis credits for much of the planet's regulatory ability (more on this in the next chapter). Algae draw down carbon dioxide as they create tissue. By using carbon dioxide from the water, algae help create a gradient that can pull more carbon dioxide from the air above. When their short lives end and any remaining algae start to rot, photosynthesis shifts into reverse. Decay sets in: The carbon in dead algae links with oxygen in the water to re-create carbon dioxide. The ongoing decay depletes local oxygen supplies. The dearth of oxygen in the waters around a bloom can suffocate or repel life forms that otherwise might dine on algae, living or dead. The lack of oxygen can limit decay as well. If even a small fraction of the algal bloom escapes decay to land on the seafloor, some of this carbon gets a sea burial—in some cases, alongside the carbon contributions from dead bottom dwellers or oxygen-starved fish. Not a pretty sight, but potentially a way for Gaia to draw down airborne carbon dioxide.

Along with stirring up plant fertilizer from deeper waters and seafloor sediments, hurricanes shift nutrient-rich sediments from land to sea for marine plants to exploit. For instance, Hurricane Gilbert's passage in 1988 pulled an estimated 92,000 tons of sediment into Jamaica's Hope River that September—twenty to thirty times the usual monthly quota based on September values for two subsequent years. Because hurricane rainfall tends to be intense yet long lasting, the floods it produces often carry a disproportionate amount of sediment and carbon compared to other rainfall events. Some of the sediment from mountains and valleys eventually settles down into deltas, wetlands, and the ocean.

Hurricane Katrina transported enough sediment to coat streets and the floors of buildings throughout flooded regions of Louisiana. I heard about some local manifestations of this when I stopped at a convenience store at the Exxon station in Leesville, a small southern Louisiana town on a tongue of land formed by Mississippi River sediments. In the course of laugh-filled conversation on a late Friday afternoon in December 2005, I mentioned to the group of locals chatting over cans of Budweiser that the people in Leesville seemed to be taking the storm with a good sense of humor. "Sure, now we are," said one man. It was tough to chuckle in the immediate aftermath, added Dodie Thomassie, a longtime employee who grew up in the area. "The water was five and a half feet in here," Thomassie said, pointing to where the waterline had reached on the wall. I looked around, marveling at the spotless white walls and clean shelves stocked with fresh provisions like dish soap, tuna, and soup. "And we had a four-inch layer of stinky mud on the floor," she added. Hurricane Katrina also deposited an eight-inch layer of mud on the Mississippi town of Hancock (near Biloxi), according to a September 7, 2005, *New York Times* story. Sediment layers on paved streets and in buildings are easier to measure, but comparable deposition layers also make their way to mangroves, bayous, and coastal waters. Even more sediment used to arrive before the levees and dams intercepted the flow to the sea. While annoying to building owners, these sediments and the nutrients that come with them have helped make the Louisiana bayou one of the world's most productive ecosystems.

This outpouring of sediment can leave a hurricane signature on the seafloor, especially in coastal regions. Studying sediment cores from the Everglades and Florida Bay, researchers Woo-Jun Kang and John Trefry found evidence for the passage of three hurricanes: Donna in 1960, an unnamed hurricane in 1948, and Hurricane Labor Day in 1935. All of that hurricane destruction and production left telltale signs on the ocean floor. For one thing, the hurricane sediment layers held roughly half the usual ratio of phosphorus to carbon, signaling it had been scavenged by life for phosphorus, a nutrient that promotes plant growth. For another thing, hurricane years left behind thicker sediment deposits than non-hurricane years. Kang and Trefry found hurricane layers as thick as 10 inches in the sediment record. That's pretty thick, considering scientists measure mid-oceanic sediment layers in millimeters or even micrometers. Finally, hurricane sediment deposits generally contained two distinct layers: a lighter one of shells and other marine-based calcium carbonates, topped by a darker layer of land-derived plant matter and soil. In the dark layers, Kang and Trefry found microscopic bits of root hairs from nearby mangrove forests.

Even the logs carried from forest to sea during hurricanes share nutrients to boost marine productivity. Naturally formed rafts of logs carried to the sea during storms typically float around the ocean for a year or so before they sink. During this time, they serve as a floating feast for an ecosystem of fish, including the ever-popular tuna. In fact, tunas' attraction to seaborne logs has inspired some fishers to launch their own log rafts as tuna-locating devices. Log rafts of any source can turn into carbon stores as well if they escape decay during their eventual journey to the seafloor. Not many creatures have the talent for turning wood into food demonstrated by termites. Further, lack of oxygen in the deep ocean and other factors limit the decay of waterlogged wood. That's why sunken ships can endure for hundreds of years at the bottom of the sea.

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Back on land, hurricanes similarly drop loads of nutrients onto the forest floor. Their winds knock down trees and branches, leaving them strewn across forest paths and city streets alike. The floods and landslides that come with hurricanes spirit off tree trunks and branches, sometimes depositing them under soil, in riverbeds, or on the ocean floor. While these logs languish, the trees that remain alive—and even many initially taken for dead—put on new leaves. At the same time, fast-growing pioneers shoot up in pockets of sunlight created by the downfall of other trees. For these reasons, forests struck by hurricanes can act as "carbon sinks," pulling carbon dioxide out of the air and into the pool of earthbound carbon. That's what research efforts at the International Institute of Tropical Forestry (IITF) in Puerto Rico have shown. Hurricanes create a carbon sink that lasts for at least decades, surmises longtime IITF director Ariel Lugo.

"The beauty of hurricanes is that they create fast-term regrowth, with ongoing storage. I think it's nature's way of readjustment," as Lugo put it during a telephone conversation in 2006. I first met Lugo in 1989, when he zoomed up on his motorcycle to help me get started on the IITF internship that brought me to Puerto Rico about a week before Hurricane Hugo. After the hurricane struck, it looked like the apocalypse. With all the barren trees, I almost expected to see smoke rising from the forest floor. Yet the "fragile rain forest" soon demonstrated a phoenix-like ability to rise from its ashes. This rapid response differs from the lingering destruction that can follow burning or clear-cutting of tropical forests.

Hugo downed about 44 percent of the trees in the hardest-hit section of the Caribbean National Forest. That's what Lugo and a host of other IITF researchers documented in a December 1991 special issue of

Biotropica about the hurricane's impact on the local rain forest, known as the Luquillo Experimental Forest in the scientific literature. (Here and throughout this book, I will use the term "rain forest" in the sense of the public vernacular to encompass both moist forests and wet forests and the term "tropical forests" when including dry forests as well.) With their branches and leaves shorn off, many remaining trees resembled telephone poles. Yet within seven weeks of Hugo's strike, all the living trees had put on a new set of leaves, ecologist Lawrence Walker reported. Over the next year, he found that about 80 percent of damaged trees had resprouted. Trees that had snapped in half sent out new shoots from their broken trunks, while many of their uprooted brethren converted some of their remaining branches into saplings. Similarly, researcher Katherine Yih and her colleagues found rampant resprouting among tropical trees in a million-acre section of the Nicaraguan rain forest struck by Hurricane Joan in 1988. Joan's 156-mile-per-hour winds had downed more than three-fourths of the trees in their research sites and stripped the leaves off most remaining trees. Four months later, about 83 percent of the tropical hardwoods had resprouted. Only a quarter of the trees, mainly pines, had failed to resprout. Apparently many tropical hardwood trees have evolved to take hurricanes in stride.

Back in Puerto Rico, the jungle's miraculous revival repeated itself after Hurricane Georges in 1998. Immediately after the storm, we had to chainsaw our way through the deadwood to get down from my friends' mountaintop home outside Luquillo. We could barely walk three strides without coming across another fallen tree or huge branch. My research across Puerto Rico over the next few months showed Georges had downed some 20 percent of island trees, although the damage ranged from 1 to 92 percent depending on species and location. Yet within four weeks, so many leaves had grown back that I had to abandon my plan to compare canopy leaf loss among plots. Although I didn't officially tally resprouting from Georges, many of the broken or fallen trees I encountered also showed renewed signs of life in subsequent months.

Cities as well as forests deal with loads of downed wood during hurricanes. When Georges swept through Puerto Rico, it left behind about 80 million cubic feet of debris in urban areas. Hurricane Katrina reportedly left behind about 1.6 billion cubic feet of debris in Louisiana alone. Along with debris from gutted homes, deadwood covered the streets of New Orleans. "There were so many trees down, you couldn't even drive in the city at first," recalled Joe Braun, a saxophonist with the Jazz Vipers who described his Katrina experience between sets in the French Quarter. "All the live oak trees lost branches. They've got branches as big as trees. They were all over the street," he remembered. Even four months later, some uprooted trees continued to litter the cityscape, including a live oak with a trunk the size of two refrigerators. It had gently landed on the house next door without doing any apparent damage. Despite all the downed urban trees, only two Katrina-related deaths resulted from falling trees, both in Florida. By December, many of the city's standing trees sported fresh foliage. Clearly the trees were doing their part to "Re-New Orleans," as the bumper stickers instructed.

The revival of barren and even fallen trees represents only one aspect of a burst of plant productivity that surges through forests after a major hurricane. In post-Hugo Puerto Rican forests, incredible growth rates continued for five years straight. Annual productivity rates were roughly triple the usual rates, as documented in a thorough study led by then-IITF researcher Frederick Scatena, one of my mentors and now chairman of the University of Pennsylvania's Earth and Environmental Science Department. He and his co-authors projected that the aboveground vegetation would reach its pre-hurricane biomass (that is, collective dry weight) within another two years if growth continued at the rate measured during the five-year study. These hurricane-impacted forests do tend to be smaller in stature than equatorial tropical forests that do not face hurricane winds on a regular basis. Still, modeling work by Robert Sanford Jr. and colleagues suggests that repeated hurricane hits increase the forests' overall productivity. In their model, this occurs largely because the fallen wood increases the amount of carbon stored in the soil (a topic of chapter 6).

At the bottom of landslides or other places where lack of oxygen limits decay, many kinds of wood can remain intact for centuries or even millennia. Decay requires oxygen, as mentioned earlier, and oxygen runs in short supply at the bottom of a 30-foot pile of soil. (The same holds true for most landfills, where the remnants of urban trees often meet an unfortunate end as wood chips.) Landslides abound during heavy rains, especially when those rains come with hurricane winds that uproot mountainside trees. Hurricane Hugo triggered a landslide for roughly every 10 acres in a 2,500-acre section of Puerto Rico's Caribbean National Forest surveyed by geologist Matt Larsen, working with lead author Scatena. The largest one moved about 1 million cubic feet of soil and debris into a nearby river. During Hurricane Mitch, about 200 million cubic feet of soil shifted in El Berinche landslide, taking down an entire neighborhood in Tegucigalpa, Honduras. Although they can usher in tragedy from the human perspective, landslides can create local pockets for carbon storage. And hurricanes create landslides.

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In short, hurricanes launch processes that play a role in cooling our planet. In the biological realm, hurricanes contribute to carbon sinks by burying logs, soil, and sediment in landslides, the ocean, and anywhere they can better escape decay. Hurricanes also heave logs onto the forest floor, where they can languish for decades—perhaps even centuries if they are large and decay resistant. While the fallen trees and branches decay over varying lengths of time, the natural hardwood forests quickly revive—often into one of the most productive phases of their existence. Marine plants, too, thrive in a hurricane's wake, albeit on a shorter time scale. Hurricanes make waves that churn up nutrients in deep water and coastal sediments. The rains and floods that come with hurricanes pull carbon-containing sediment from the land into the ocean, where it can nourish marine life or wind up in long-term storage on the ocean floor. For every molecule of carbon locked up in vegetation or buried in deep storage, there's one fewer molecule free to form heat-trapping carbon dioxide or methane. Physically, hurricanes cool the ocean surface as their winds stir chillier waters from below into the mix. Their rains also disperse heat. The many cooling features of hurricanes help explain why they can help Gaia resist global warming.

With all that, the time scales involved in hurricanes' cooling actions do not necessarily match human needs. Mainly, hurricanes cool the world's two warmest regions—the tropics and subtropics. In so doing, they can actually warm regions closer to the poles. Even in the tropics, the cooling wakes hurricanes leave behind often seem to warm back up in a matter of weeks under the sun's hot glare. Although it seems logical, by extension, that these storms cool tropical seas on longer time scales, the idea that they could help from one season to the next remains speculative at this point. Similarly, a hurricane's boost to plant growth makes only the tiniest dent in global carbon dioxide levels—even if you add the efforts of marine and land plants together. The amount of carbon dioxide a hurricane pulls down to earth represents less than a drop in the bucket considering how much exists in the atmosphere. But any process that pulls some of these molecules back down to earth could help moderate global warming over the long term.

Hurricanes could help balance carbon dioxide levels at the scale of perhaps decades, but more likely centuries. Yet people are putting more carbon dioxide and other heat-trapping gases into the air on a daily basis, throwing the balancing act out of whack. Every year, carbon dioxide levels climb by about half a percent, on average (and rising), over their existing levels. We'd all be running for the hills far from the coast if hurricanes were going to control this excess. More realistically, hurricanes could help restore balance once we have our fossil-fuel habit in check. Given the growing sentiment that we're launching an irreversible warming of Earth, it's comforting to know that Gaia has at least some defense mechanisms for dealing with the temperature rise, even if hurricanes lurk among them.

Hurricanes are both a symptom of global warming and one of its cures. It's a tough pill to swallow. We would prefer if the antidotes to rising temperatures came in easier-to-take forms, like the minuscule tablets of homeopathic medicine. But sometimes a body—even a planetary body—needs strong medicine. Hurricanes certainly pose a risk to the system, but they serve as one of Gaia's natural defenses to rising temperatures.

An informal poll of family and friends indicates that Gaia theory remains unfamiliar or incomplete to many Americans, and even some environmentalists. Among scientists, too, Gaia theory takes many different forms, including Earth system science. So, before delving into other ways the entity on which we all depend responds to changing temperature, it's time to get better acquainted with the theory that our living planet has a built-in system for climate control.

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