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What Is the Upper Limit?

The breath you just took contains over 400 parts of carbon dioxide per million molecules (ppm) of air.[1] People living at the start of the Industrial Revolution would have inhaled about 278 ppm. Since then, levels of CO_2—the leading greenhouse gas driving changes in the climate—are on course to double owing to the relentless burning of fossil fuels. In a worst-case scenario, CO_2 concentrations will exceed 900 ppm by the year 2100. Unfortunately, that scenario is within the realm of possibility. Carbon dioxide is the natural product of cellular respiration in animals and plants. Fossil fuel emissions from human activity over the past two centuries now threaten our atmosphere, oceans, and life on Earth. In spite of the impacts—extreme heat and wildfires, catastrophic floods and storms, massive crop failures, and unrelenting biodiversity loss—some experts have made the claim that human cognition operates on a very narrow spatiotemporal scale; we are unable to see—let alone deal with—the flood of changes that we have unleashed. Our horizons are so limited, the argument goes, because *Homo* *sapiens* never evolved enough mental bandwidth to apprehend a long-term future. Our ancestral selves were mainly preoccupied with the "immediate band, immediate dangers, exploitable resources, and the present time."[2] So here we are, built to be blindsided in a new and hostile world. Yet the claim of cognitive barriers is just that—a claim—and, in any case, overcoming such barriers to responding to all but our short-term needs is not the real challenge. Rather, we need to ask how narrowed self-understandings prevent us from effectively addressing the problem of climate change, leaving us stranded in a present that may not be survivable.

More than a century's worth of research undercuts the idea that a bias toward inaction in a high-CO_2 world is preordained. During World War I, when submarines were first widely deployed in warfare, a US Navy sanitary officer and surgeon named R. C. Holcomb worried about carbon dioxide displacing oxygen in breathable air in these sealed underwater capsules. Carbon dioxide is a colorless and odorless gas, so it is tempting to think that its risks cannot be sensed. Holcomb questioned this assumption, writing, "We cannot forget that we are at the bottom of an aerial ocean and saturated with its gases." He expressed concerns over "men obliged to breathe their own expired air over and over again."[3] More than a hundred years later, we think of carbon dioxide in more distant (atmospheric) terms, an input to be tracked or mitigated in climate change scenarios. Its physiological impacts are harder to grasp. Holcomb made his observations at a time when, in military and medical spheres, new instruments were being devised that could scrub carbon dioxide from closed environments. Consider the American pharmacologist Dennis Jackson, who wanted to make anesthesia gas accessible to his poorer surgical patients. Breathing chambers of the early twentieth century delivered

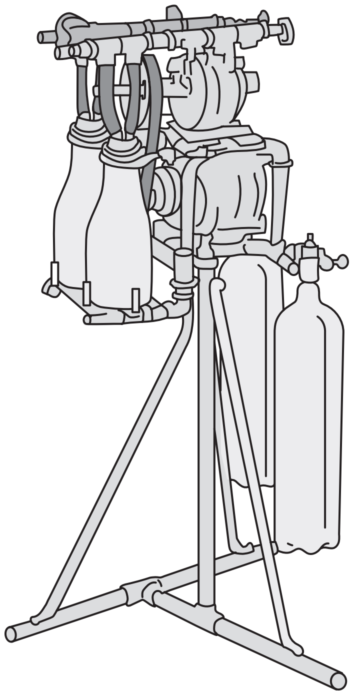

FIGURE 1.1. Jackson CO_2 Absorber (redrawn from image courtesy of Wood Library Museum).

expensive nitrous oxide, but they also leaked it. Hoping to make its delivery more efficient, in 1914 Jackson invented a closed circuit chamber to trap the nitrous oxide. But it also trapped patients' exhaled carbon dioxide gas. When he added soda lime, which absorbed the gas, patients could rebreathe expired air. It so happened that the "Jackson CO_2 Absorber" was invented in St. Louis, a city once saturated with coal smoke. The absorber worked so well that when Jackson tested it on himself, he reported having "the first breaths of absolutely fresh air he had ever enjoyed in that city."[4]

Like atmospheres, our bodies require careful calibration between oxygen consumption and carbon dioxide production. The amounts of carbon dioxide that are present in our arterial blood and exhaled in our breath are always maintained reciprocally through a partial pressure gas exchange. This exchange is critical to survival. When the gas accumulates in our blood during sleep, our bodies signal an imbalance (by snoring, waking up, breathing abnormally deeply, or, if the lungs' ability to remove CO_2 is seriously impaired, exhibiting asthma or respiratory failure). Doctors use CO_2 saturation as a prognosticator for "time to death" in terminal patients.[5]

Too much CO_2 in the blood is a sure sign of imminent cardiac arrest or death.

So immediate are visceral responses to carbon dioxide overload that researchers have attributed to it involuntary reactions of all kinds. In work that was a precursor to his studies on "voodoo" death,[6] Walter B. Cannon, a professor of physiology at Harvard from 1906 to 1942, experimented on dogs to show how distress and panic increase the body's production of carbon dioxide, which he famously called the fight-or-flight response. "Great exertion, such as might attend flight or conflict," he wrote, "would result in an excessive production of carbon-dioxide."[7] More recently, researchers have found that they can simulate a variety of mental infirmities, from anxiety and panic disorders to combat-related stress reactions, by exposing human subjects to carbon dioxide–enriched air.[8]

Distress, an induced panic, or even cardiac arrest: our bodies respond to this insensible gas, whether we're conscious of its presence or not. Given the wide-ranging effects CO_2 has on biology, we can ask how much of a threat to physiological equilibrium we are willing to tolerate. In one respect, it is difficult to say: while the unconscious systems of our bodies are adept at signaling intolerance, the conscious ones are often too sluggish to recognize or fend off the danger.

Let's then move from the autonomic realm to the question of how awareness and assessment of CO_2's risks have evolved, drawing examples from modern agriculture and war. In 1954, when two Kansan farmworkers descended into a silo full of beans, barley, and oats, the gas released from the fermenting silage killed them. Silos notoriously contain high amounts of carbon dioxide, giving no warning of their lethality to people entering them.[9] So farmworkers developed homespun techniques to test for gas buildup before entering these structures.

One involved lowering a candle into a silo to see whether its flame died out (this occurs when carbon dioxide gas displaces oxygen needed for combustion). Another entailed suspending a warm-blooded animal in the structure to see whether it fell unconscious. When the sentinels' limp bodies were fished out of the silos, it was found that "an exposed guinea pig was unconscious within 30 seconds and a rabbit within 60 seconds."[10]

In an early study (1914) of a carbon dioxide accident on a farm, investigators found four men dead in a silo in Athens, Ohio. Coworkers reported that these men had entered the silo to tamp down new silage, but "within about five minutes the men inside were not responding to the shouts of their coworkers." Accident investigators noted CO_2's ability to trick the senses, writing that a "more peaceful and inviting scene could not be imagined than the warm, pleasant smelling green silage within."[11] Sensory trickery of this kind also has its uses: for decades, farm managers have been exposing livestock to high levels of carbon dioxide to anesthetize them before slaughter, a method that animal welfare advocates consider more humane than electrical stunning.[12]

As examples from agriculture illustrate, knowledge of the effects of carbon dioxide is carved into modern life. That humans can do no more than deny them because we as a species cannot see past our arms does not add up. History, too, refutes this notion. When incendiary bombs were dropped during World War II, European cities were flooded with clouds of toxic gas (including CO and CO_2), killing untold numbers of people for whom overcrowded air-raid shelters provided no escape.[13] In July 1943, the air raids on Hamburg ignited massive fires. The author of *The Night Hamburg Died* (1960) describes what transpired in the shelters from these torrents: "Sealed into their cellars, huddling behind heavy doors, they have closed themselves off from the outer world and the oceans of fire splashing around and over their warrens. No flame ever touches them, but not a man, woman, or child survives. Not a single living soul. Not a human being, an animal, not even the smallest rodent, not a single insect, survives."[14]

There was also neither warning nor escape when, on August 21, 1986, an underground bubble of carbon dioxide erupted in Lake Nyos, an active crater lake in Cameroon, releasing a low-hanging gas cloud that killed over seventeen hundred people.[15] One survivor, knocked unconscious for several hours, described his experience when he woke up: "I could not speak . . . I could not open my mouth because then I smelled something terrible . . . I heard my daughter snoring in a terrible way, very abnormal." He continued: "When crossing to my daughter's bed . . . I collapsed and fell . . . My daughter was already dead . . . I got my motorcycle . . . As I rode . . . I didn't see any sign of any living thing."[16]

An American biologist who studied the Lake Nyos disaster (and another at Lake Monoun in Cameroon two years later) conveyed to me some of the physical and sensorial aspects of total exposure: "At the heart of the cloud released during the Lake Nyos and Lake Monoun disasters, the concentration of CO_2 was 100%—that is, the CO_2 had displaced all of the normal air that we breathe." Concentrations of CO_2 above 15–20 percent will cause suffocation and death in animals and humans.[17] In a lower range of 10–15 percent, delusions can set in. Here, as the scientist described to me, "CO_2 can act as a sensory hallucinogen, such that people feel and smell things that aren't really there." Where the CO_2 concentration hovered just below the lethal limit, some Lake Nyos survivors reported smelling rotten eggs or gunpowder and feeling very warm. "The rotten eggs smell is unmistakably a smell of sulfur gases and feeling warm is also associated with volcanoes producing heat," he noted. "However, our analyses showed that there were no sulfur gases released (or very little) during the disaster, and that the gas burst was not associated with heat release from a volcano."[18]

In other words, the gas cloud the biologist describes was full of sensory bewilderments, resulting from a freak geophysical event the likes of which most of us will never experience. But I knew someone who may have lived through something comparable. My father was a twelve-year-old child refugee from a small village in Ukraine—one among hundreds of thousands who fled the country for displaced persons camps in Western Europe when the Soviet and German forces met in 1944. Allied forces conducted aerial bombing raids, targeting industrial plants and railway stations as well as fleeing civilians, as he would point out. The civilian refugees were a hundred miles into their trek when one of the bombs from a shuttle bombing operation fell near a border town, hitting an underground tunnel that served as a makeshift bomb shelter. His older sisters had not made it to the overcrowded shelter-turned-death-pit—but he had. Through a child's eyes, he described to me what it was like to be packed inside and, in his words, "what people's lungs look like when they are gasping for breath." By some miracle, the little boy found himself near a tiny airhole. Taking in small sips of fresh air, he observed the terrifying distensions all around him. He lost consciousness and, along with other presumed-dead bodies, his was thrown onto a flatbed truck. The high-pitched voice of his oldest sister calling out his name (Misio!) awoke him, and then (a detail that as a child I could hardly fathom) he stood up from the pile of bodies and got off the truck. The small amount of oxygen from that hole in the tunnel prevented the extreme CO_2 concentrations from killing him.

This near-fatality conjoins histories of human breath and pyrogeographies of modern warfare. In his essay "Air War and Literature," the writer W. G. Sebald depicts the absolute destruction wrought by the Allies' aerial bombing of European cities in World War II. There was a narrative vacuum. German writers, Sebald argued, "would not or could not describe the destruction of the German cities as millions experienced it." The bombings left "31.1 cubic meters of rubble for every person in Cologne and 42.8 cubic meters of rubble for every inhabitant of Dresden."[19] Adding to the physical destruction, the Hamburg air raids produced a massive urban firestorm, five kilometers in height and covering seventeen square miles.[20] Winds produced a high-velocity fire whirl that still perplexes fire scientists today. Of Hamburg's obliteration by fire, Sebald wrote: "At one twenty a.m., a firestorm of an intensity that no one would ever before have thought possible arose. . . . At its height, the storm lifted gables and roofs from buildings, flung rafters and . . . billboards through the air, tore trees from the ground and drove human beings before it like living torches."[21] Scenes like these, along with unrecognizable ecological synergies, are at the heart of these overlooked embodiments of total war.

An estimated forty-five thousand died in the aerial bombings. Their incendiary effects, along with those of nuclear weapons, led to an "unprecedented boom in the research of wildland fires."[22] But the boom was short-lived. In the 1950s and 1960s, when Cold War researchers were conceiving of radioactive fallout shelters to protect people in the wake of nuclear attacks, they overlooked the fact that shelters would ultimately be "useless, largely because of firestorms."[23] They narrowed the scope of the hazard to a mechanical balancing of oxygen supply with carbon dioxide removal in closed environments. How long could occupants live in a nuclear fallout shelter? Studies tested chemical

FIGURE 1.2. Bombing of Hamburg. Avro Lancaster heavy bomber, World War II, 1939–1945 (Science & Society Picture Library).

carbon dioxide removal as a method of prolonging occupancy after breathable air dissipated. In one study, two adults sat in a fallout shelter as researchers monitored oxygen consumption and carbon dioxide accumulation.[24] In hour one of occupancy, the oxygen remained at 20 percent. In hours two and three, it dropped to 19 percent. In hour four, it was at 18.5 percent. Carbon dioxide concentrations rose steadily, from 0.5 percent in hour one to 1.7 percent in hour four. In a bomb shelter packed with hundreds of people, this rate of increase would likely result in CO_2 gas concentrations in the range of 10 percent, if not more, certainly high enough to cause them to fall unconscious or die.

As with any other noxious gas, carbon dioxide is classified as an occupational hazard; its levels are monitored and federally regulated in various industrial settings to insure safe respiration. The US Department of Labor, for example, considers 400 ppm to be the outdoor norm for CO_2 exposure, and 800 ppm the indoor norm. According to a CO_2 monitor salesman I spoke with, 1,500 ppm "is when you start to see effects." In fact, the majority of his sales were to school districts because of concerns about the dangers of carbon dioxide to children's school performance: "We need to break up the CO_2 concentration in schools." At 5,000 ppm, metabolic stress and narcosis or a depressed state of consciousness can set in.

Seen through its somatic history, carbon dioxide comes to be palpable through industrial techniques and standards developed to exploit its potentials, mitigate its harms, or protect breath. That history consigns humans and nonhumans (rodents, cattle, and refugees) to the structures of research and the rubble of modern war. It also becomes an exercise in securing what the philosopher Achille Mbembe calls "the universal right to breath." Following the death of George Floyd, whose public assassination by police chokehold ignited protests against racist policing and anti-Blackness around the world, Mbembe writes, "Caught in the stranglehold of injustice and inequality, much of humanity is threatened by a great [suffocation]" and this sense "spreads far and wide."[25]

Today, threats to breath are all around as "[w]e are adding planet-warming carbon dioxide to the atmosphere at a rate faster than at any point in human history since the beginning of industrialization."[26] CO_2 toxicity has been calculated extensively (from the science of the fight-or-flight response to occupational safety and even bomb shelter survival). When it comes to planetary risk, a terrible disjuncture remains between the scale of the threat and the pace of collective efforts to stop its cascading impacts. There is a failure of imagination, which the writer Amitav Ghosh calls a "great derangement," when it comes to connecting the burning of fossil fuels and CO_2 rise to our altered present. Politicians with no vision beyond the next election cycle normalize the derangement, or the idea that our horizons, so truncated, will never allow us to meet conditions where they are.

Meanwhile, as we will see in this book, earth scientists are getting a better handle on how increases in CO_2 and other fossil fuel emissions threaten to destabilize entire Earth systems. Having passed a particular threshold, ocean acidification—caused by the overabundance of CO_2 in the seas—will trigger widespread fish extinctions due to diminishing coral reef ecosystems (which sustain roughly 10 percent of the world's fisheries). On land, rising temperatures associated with increasing CO_2 concentrations threaten to wipe out agricultural production in some areas.[27]

Carbon dioxide is absorbed in the atmosphere and by forests and oceans. But what kinds of worlds will be habitable once parts of the Earth system have lost their ability to "scrub" carbon dioxide? Researchers are unsure about where the CO_2 will go. The future of Earth's CO_2-offsetting reservoirs (or carbon sinks) is uncertain—nearly a third of them are saturated or have disappeared. This occurs at a time when CO_2 levels routinely exceed 400 ppm, higher than they've been since "three to five million years ago—before modern humans existed."[28]

I measured levels of the gas in my everyday (pre-COVID) surroundings with a handheld CO_2 monitor that I purchased online. There was a surprising amount of variability. The CO_2

in my small office measured 608 ppm; a lecture hall, 955 ppm; a room where I met with a group of incoming college students, 1,027 ppm. When I stuck the monitor outside my office window, it read 388 ppm. At home, levels varied from 402 ppm to 1,339 ppm. When I exhaled right into the monitor, it jumped to 3,994 ppm. Variability, I learned, is the very thing that has allowed land animals to survive in milieus with relatively high levels of CO_2—and humans to dominate the planet. If the CO_2 is too high in one setting—say, in a classroom or office—we will know it (perhaps not consciously) and eventually leave the room or open a window for fresh air. Even if we start hyperventilating, we can usually recover, which, strictly speaking, means returning our partial pressure of carbon dioxide (a measure of carbon dioxide in arterial blood) to a normal level.

As air-breathers, humans have a high partial pressure of carbon dioxide (P_{CO_2}). Our bodies are equipped to deal with variable CO_2 levels. In the constant adjustment to variability, we normally have the luxury of forgetting that without such adjustment, we would soon be dead. Contrast this with aquatic animals, for whom "the difference in P_{CO_2} between inspired and expired medium," in this case, water, is much smaller.[29] The smallest rise in CO_2 in any aquatic system can trigger a state called hypercapnia, from the Greek *hyper* (over) and *kapnos* (smoke) and occasion a massive fish die-off. Aside from the very few fish that can air-breathe (using their mouths, esophagi, or stomachs to trap air when water becomes oxygen-deprived), water-dwellers, for the most part, can't compensate for variability in their aquatic environments the way that air-breathers can, nor can they escape water in which they cannot breathe. Readers may have seen the workings of hypercapnia in oxygen-depleted ponds or lakes. One day, everything seems normal, as life teems just beneath the surface; the next day, fish underbellies cover the entire lake as far as the eye can see.

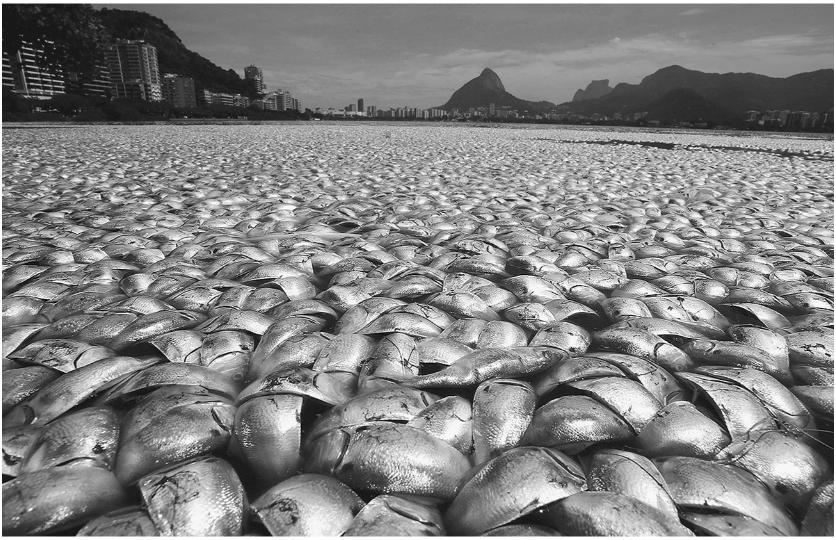

FIGURE 1.3. Lake ecosystem regime shift after human pollutants decrease oxygen levels, Rio de Janeiro, 2013 (Reuters/ Alamy/Sergio Moraes).

We may find comfort in the fact that we are not fish. Air is a much more forgiving medium than water as far as respiratory physiology goes. But when it comes to humans and fish, how should we conceptualize differences in survival capacities amid elevated CO_2 levels? Is it a matter of physiological difference (that confers some seemingly inherent advantage in one kind of animal and not another)? Or is it a matter of an environmental difference (that will always provide one kind of animal and not another with escape hatches within variable milieus)? Setting species-specific distinctions aside, is there a place and time in which human and fish fates might converge, pushing us toward some edge, some horizon beyond which existence ceases to be viable—call it extinction—without our even noticing?

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