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Heat

That the railway transport cars were labeled “SS” trains was only the first of several unfortunate parallels with an earlier forced migration of comparable scale. In what would be the largest domestic evacuation of a displaced population since World War II – and perhaps in human history – India’s Shramik Special trains would transport an estimated 5,000,000 migrant workers over the period of a few weeks in May 2020 (Figure 1.1) [1]. The need to return a large population of migrant laborers from India’s largest cities to their home states during a pandemic lockdown would necessitate extreme measures. The need to do so during one of the most intense heat waves on record would render the extremity of conditions on these trains unimaginable to anyone reading these pages. With temperatures in some regions of India exceeding 122°F [2], and air-conditioned railcars a luxury unavailable to most laborers, the train interiors were approaching, quite literally, the temperature of an oven. The total number of deaths from heat exposure is not known but press accounts reveal a regular removal of bodies from the SS trains [1].

While India is widely recognized as exhibiting a unique vulnerability to heat waves, its cities do not rank among the hottest on the planet. Desert cities of the Middle East, Africa, North America, and Australia all experience higher summer temperatures than the hottest of Indian cities. What renders Indians uniquely vulnerable to heat is not the extremity of temperature alone but a combination of very high temperatures and very high humidity. Like a winter coat in summer, humidity does not elevate the air temperature; it impedes the efficiency with which our bodies shed heat – amplifying the effects of temperature. A comparison of record temperature and heat index values, measuring the combined effects of heat and humidity, reveals the potential extremity of humid environments. The highest temperature yet recorded on Earth – 134°F in Death Valley, California – is about 10 degrees *lower* than

Figure 1.1 Laborers on Shramik Special train in West Bengal, India, May 24, 2020. Sanjoy Burdwan/iStock.

maximum heat index values measured during a recent heat wave in Delhi [3,4]. For Indians, humidity is the sharp end of the heat spear.

Highly adaptable to a wide range of climatic conditions across the planet, humans are surprisingly vulnerable to the most minimal of shifts in our internal physiologic state, with a rise or reduction in our core body temperatures of just a few degrees sufficient to induce death from heat or cold. Our principal adaptations are non-physiologic – buildings insulated against extreme temperature fluxes; clothing adjusted to the season; a cold shower on a hot day. When these external adaptations fail to guard against a swing in our core body temperatures of just a degree or two, our bodies deploy a small number of physiologic responses to maintain thermal equilibrium. In response to a falling core temperature, we shiver. Produced through a rapid tensioning and relaxing of skeletal muscles, shivering leverages the body's energy stores not for the usual purpose of carrying out work but rather for the waste product of muscular action: heat generation.

In response to a rising core temperature, we sweat. And, here again, in sweating the body makes strategic use of what is typically a waste product to maintain thermal equilibrium. Acquired directly through the ingestion of liquids and indirectly as a by-product of cellular respiration (the chemical processing of food energy), excess water is routed to the bladder for excretion. When conditions warrant, however, excess water can be excreted to the skin via sweat glands to protect against the incoming heat from the Sun and atmosphere.

While the water itself does not provide a cooling effect, its evaporation into the surrounding air diverts heat energy from the Sun and atmosphere from warming the skin to bringing about a phase change in water. Just as a boiling pot of water will maintain a constant temperature of 212°F as long as water remains to fuel a phase change to water vapor, moistened skin can suspend a rise in temperature with the continuous excretion of sweat.

Among the most powerful tools devised by the biophysical world to maintain homeostasis in mammals, or tolerable temperatures within ecosystems, this phase change in water exploits the Earth's natural conveyance system for cycling water between the biosphere and atmosphere to also cycle heat. Only when the water vapor cools and condenses back into liquid water, which occurs by rising to a higher altitude in the atmosphere, will the heat energy entrained within the vapor be released again to the environment – far removed from the vulnerable surface of the skin on a hot day.

High levels of atmospheric humidity are an acute threat to humans in hot weather not because humidity elevates the temperature of the air but because it impedes the efficiency with which water can evaporate from the skin's surface. Like a bowl of water filled to its rim, any further addition of liquid will cause the pool to overtop the vessel. As the atmosphere approaches 100 percent humidity, there is simply no additional capacity to absorb more water vapor. Under these conditions, water secreted by sweat glands can only pool on the surface of the skin, running off without extracting much heat from the surrounding air and failing to arrest a rise in core body temperatures. Once core body temperatures surpass 104°F, heatstroke – a rapid-acting and life-threatening condition – becomes likely [5].

Heat stroke is so named because it results from a starving of the brain of blood. Much like the more common ischemic stroke, resulting from a blood clot in the brain, a heatstroke also depletes the flow of blood to the brain – not from a physical blockage but from a massive diversion of blood to the body's extremities in a hypothalamic effort to dissipate heat back to the atmosphere. First characterized as a stroke by the ancient Greeks due to a sudden loss of consciousness – as if "struck down with violence" [6] – any rapid depletion of blood from the brain will likely prove fatal absent an immediate restoration of normal blood volumes. In the instance of heatstroke, clotting assumes the form of a blockage in the dissipation of heat from the skin's surface, with atmospheric humidity serving as the clotting agent.

The unique extremity of heat and humidity found in India is characteristic of a larger region stretching from the Arabian Peninsula across South Asia, where relatively shallow seas, such as the Persian Gulf and Red Sea, do not support as much cooling through deep water circulation as the Atlantic or Indian Oceans.

Unable to distribute absorbed solar energy as effectively through a deeper water column, these shallow seas give rise to very high rates of evaporation, fueling, in turn, the transport of unusually humid air across the subtropical deserts of the Middle East, Pakistan, and northern India. What results in the summer months is the most intense combination of extreme heat and humidity with densely populated settlement as found anywhere on Earth.

The implications of this combination of extreme heat and humidity for those unacclimated to these conditions – for example, to invading armies across history – can be quite severe. The first known record of a catastrophic heatstroke event is provided by the Roman historian Dio Cassius, who recounts one of the most disastrous military campaigns of the Roman Empire, waged against a resisting population on the Arabian Peninsula in 24 BC. Entirely unprepared for the levels of heat and humidity commonly experienced in proximity to the Red Sea, more than half of the Roman army was lost to heatstroke before a single combatant was encountered. Cassius writes that "the malady proved to be unlike any of the common complaints, but attacked the head and caused it to become parched, killing forthwith most of those who were attacked" [7].

Heat stroke was a common occurrence through the period of the British occupation of India, with troops regularly succumbing to extreme heat exposures in the cramped and unventilated quarters of transport ships. Having failed to suppress an uprising in Calcutta (now Kolkata) in 1756, 146 British soldiers were imprisoned in a small, poorly ventilated cell overnight in summer conditions. Only 23 were alive the next morning [8].

And in more recent history, an estimated 20,000 Egyptian soldiers were lost to heatstroke during the Six-Day War with Israel in 1967, as the Egyptian army failed to supply sufficient water to its soldiers exposed to the summer heat and humidity of the Negev Desert [5].

In each of these instances, soldiers perished not only from an exposure to extreme heat but from a water imbalance – either too little in their bodies or too much in the atmosphere. What these historical narratives suggest in a world with declining freshwater supplies and rising water vapor is perhaps surprising: The greatest threat to our health from climate change is not a hurricane or a wildfire but an inability to sweat when our lives depend on it.

The Shrinking Map

One of the hottest cities in the world is also the coolest – at least along its sidewalks. With afternoon temperatures exceeding 100°F for more than four months a year, Doha – the capital city of Qatar, a small country in the Persian

Gulf region – is among the most extreme urban environments on Earth for a city with millions of residents. Compounding the heat is an average relative humidity in the summer months approaching 50 percent, resulting in maximum heat index values of about 140°F – more than sufficient to render a sidewalk stroll fatal. Despite these conditions, Doha's commercial districts are lined with high-end retail shops from around the world, complete with well-populated al fresco dining along the city's streets.

The solution to this enigma – how to provide a pleasant dining experience in an environment that exceeds physiologic thresholds for human heat stress – is to be found in football stadium design. In hosting the 2022 World Cup, Doha was confronted with the challenge of safeguarding the well-being of millions of visitors during a time of the year in which typical afternoon temperatures exceed the most intense heat wave conditions ever experienced by many traveling from outside the region. Doha adopted two strategies to address the heat threat. The first was to delay the World Cup by five months, to fall within the milder winter months of November and December. A similar strategy was adopted for the 2019 World Athletics Championships, also hosted by Doha, during which the women's marathon start time was shifted to midnight to lessen the intensity of the heat exposure (race time temperatures hovered around 90°F). More than 40 percent of the runners failed to cross the finish line, many requiring wheelchair assistance due to heat exhaustion [9].

The second strategy was to pump vast amounts of air conditioning into the football stadiums. This might sound like standard fare for large athletic facilities in hot environments, but the Doha World Cup planners had no intention of closing out the Sun and heat with a roof: The air-conditioned stadiums were open to the desert extremes. By positioning air conditioning vents immediately underneath each of the 40,000 seats in the Al Janoub Stadium – one of many newly constructed for the event – football fans could be cooled from their ankles up, before the chilled air, and the immense energy required to cool it, was lost to the desert winds. The same is true for sidewalk diners in Doha's commercial districts, where countless portable air conditioners are positioned table-side, allowing the customers and their butter pats to remain in a solid state (Figure 1.2).

Climate change is relentlessly characterized by the media, politicians, and, most regrettably, climate scientists as a temporal phenomenon – one unfolding over decades – but it is the changing spatial dimensions of current climate extremes that now most threaten us. The globally averaged environmental conditions projected for the middle or end of this century are no more extreme than those that we currently find in many parts of the planet today. If there was a tipping point beyond which the thermal extremes of cities in which millions

Figure 1.2 Use of air conditioning for outside dining in Doha, Qatar. Salwan Georges/Washington Post/Getty Images.

reside would become intolerable, we have passed it. For cities like Doha, it is only the resilience of the electrical grid that safeguards against the loss of tens of thousands of lives in a matter of hours – a collective ventilator to which every resident is now critically tethered.

While scientific terminology pertaining to life-threatening environmental conditions can be woefully understated, a recent addition to the technical lexicon bucks this trend. In the last few years, a growing number of technical papers, appearing in among the most staid journals of climate science, have included a new phrase in their titles and abstracts: *human survivability*. The use of this phrase is unusual in its seeming lack of precision, in that, given the wide range of climates in which humans have long settled – stretching from polar extremes to equatorial deserts – there are no historical ecological conditions considered outside the range of human adaptability. Yet this basic precondition for human settlement, at least with respect to heat, is no longer true.

If our geographic tolerance for environmental temperatures is surprisingly wide, our tolerable range for internal temperatures is surprisingly narrow. As any school-age child knows, just a few ticks above 98.6°F on the thermometer is sufficient to keep you off the school bus. The resulting condition – a fever – is widely defined by national public health agencies as a temperature of 100.4°F or higher, or, as more commonly measured, a temperature of 38°C. This number is remarkable both for its universality and for its circumscription. Travel the world over, from the polar-most outposts of Alaskan Inuit to the Tuareg peoples of Saharan Africa and you will find no measurable variation in the median core body temperature of healthy individuals. A fever in Moscow is measured as the same fever in Montevideo.

Beyond the constancy of this threshold, the human body can tolerate only the most minimal perturbation to its 98.6°F setpoint, and it is this immutable biological limitation that most starkly defines our present ecological circumstance. With only a single degree centigrade demarking the zone of well-being from that of illness, a shift in environmental temperatures that pushes us above this threshold constitutes a worrisome development. For the entirety of our impressive run at civilization building, commencing early in the epoch of the Holocene with the advent of advanced toolmaking, we have become quite skilled at adapting to an environment that has, with few exceptions, threatened to push our core body temperature *below* this critical threshold. We have managed environmental temperatures far colder than our setpoint temperature through technological adaptations in the form of clothing, insulated buildings, and fire-making. Indeed, it is precisely our adeptness in fire-making, in the form of hydrocarbon-driven industrialization, that is pushing environmental temperatures higher than our homeostatic temperatures.

Chief among the many challenges presented by a warming climate is this: Our tools for managing temperatures higher than our homeostatic setpoint are far more limited than those for managing temperatures lower than this threshold. Consider, for example, clothing. We have become very skilled over time in designing clothing for maximal insulation, varying both the materials and the thickness to achieve comfort in differing ranges of cold. Should a single layer of clothing prove insufficient in maintaining thermal homeostasis, we have the option of layering with additional clothing or with external insulators, such as blankets. Confronted with environmental temperatures that threaten to raise our core body temperatures, de-insulating with clothing for cooling is a much more limited adaptation than re-insulating for warmth, in that a single layer of clothing can only be removed once.

Likewise, no easily catalyzed chemical reaction for environmental cooling matches the simple efficacy of fire-building. Attainable with transportable ignition tools, plentiful natural fuel stocks, and universally available oxygen, fire is our species' most profound hedge against inhospitable environmental conditions. This is precisely the reason we have thrived in a world with environmental temperatures cooler than our homeostatic temperature in that our ability to regulate colder than optimal temperatures with fire has opened up a full planet to human migration and settlement. What equivalent tools can be transported in a backpack and combined with widely available fuel stocks to catalyze instantaneous environmental cooling in an uncomfortably hot setting? The absence of such tools, perhaps as the very product of our long-running adaptation to a cold planet, leaves us uniquely vulnerable in regions of the world in which environmental temperatures run higher than our homeostatic setpoint. And these regions are now expanding.

It is of course reasonable to observe that humans have lived for millennia in environments with temperatures periodically exceeding 98.6°F. What has changed, and only changed very recently, is our exposure to temperatures exceeding this homeostatic threshold in combination with humidity levels that inhibit our physiologic adaptations to environmental heat. While we often think of heat and humidity as positively related, with humidity levels seeming to rise during the summer months, the association between heat and humidity tends to exhibit a negative relationship, with relative humidity falling during the course of the day or course of the year, as temperatures rise. The reason for this is that relative humidity – the quantity of water vapor present in the air as a percentage of the maximum quantity of water vapor the air can carry – is directly related to the density of the air. To best grasp this association between atmospheric humidity and density, it is helpful to revisit the basic concept of temperature itself.

We associate temperature with the sensation of heat (or the absence of heat), but it can also be understood in terms of molecular motion. As the temperature of a gas or a liquid or a solid – let's imagine the handle of a stainless-steel saucepan for the moment – increases, the energetic motion of the elements that make up the saucepan increases in concert. In the case of our steel pan over a gas flame, the carbon and iron atoms present in a steel alloy will begin to vibrate with more intensity as heat is applied to the pan. This vibratory motion that starts in close proximity to the flame will be transferred along the pan to its handle as energized atoms agitate adjacent atoms in the solid material of the pan. It is the vibratory motion of the iron and carbon atoms in the saucepan handle that our hands experience as heat or as a rising temperature.

Were we to add water to the pan for boiling, the behavior of the water molecules would approximate that of the iron and carbon atoms but with one key exception: As the molecules of a liquid become energized with the addition of heat, they are free to move around within the full volume of the liquid, as opposed to vibrating in place. As the energized water molecules circulate within the pot, heat is gradually distributed throughout the body of water, as these energized water molecules displace cooler or less energized water molecules toward the heat source. This process of heat distribution via the circulation of energized molecules in a liquid or gas is referred to as *convection*.

The free movement of energized molecules in a liquid or gas via convection changes the liquid or gas in at least two respects. First, this convective movement distributes heat throughout the full volume of the liquid or gas over time, raising its temperature. Second, increasing molecular motion with rising temperature expands the volume of the liquid or gas, as repeated collisions between energized molecules create additional space between the molecules. When confined to the interior of a saucepan, the volume of water within the pan expands as it becomes heated, with a potential to overtop the pan itself. When confined to the far more expansive volume of the atmosphere, the available space between heated air molecules can increase significantly, resulting in a reduction in the density (the number of gas molecules per unit of volume) of the air.

Relative humidity will typically fall during the course of a summer day due to the decreasing density of the atmosphere with the addition of heat energy from the Sun. As the space between air molecules increases with rising temperature, the capacity of the air to carry additional water vapor also increases. If the water vapor content of the air remains fixed, the quantity of the water vapor as a percentage of the total water vapor the now lower-density air can absorb (i.e., relative humidity) will fall.

Of course, the quantity of water vapor in the air over the course of a warming summer day may also increase with a rise in evaporation from surface water and transpiration from trees and other plants. This increased evaporation, however, typically is not sufficient to keep pace with the falling density of air and its rising capacity to absorb water, and so relative humidity tends to fall over the course of a day, with lower levels observed in the late afternoon when temperatures are at their maximum.

Confronted with the need to carry out operations in extreme climates, the US military developed a new metric of combined heat and humidity in the 1950s to better forecast and characterize the risk of heat exposure. Referred to as “wet bulb globe temperature” the resulting metric is designed to more precisely pinpoint thresholds beyond which normal activities must be suspended. While indicators of combined temperature and humidity, such as the heat index, have long been measured and reported in weather forecasts, a key limitation of this metric is that it accounts for air temperature in the shade only. Shade-based measurements of temperature are desirable in that these allow for air temperature effects to be separated from *radiant* temperature effects. When we stand in the shade of a tree on a sunny afternoon, for example, we are warmed primarily by the temperature of the air. When we move away from shade, our skin is warmed both by the temperature of the air and by the direct receipt of radiation from the Sun.

In a world in which air temperatures rarely rise above our core body temperature 98.6°F, the combined effects of heat and humidity on our physiologic capacity to maintain homeostasis are of less import for human health than the threat of uncomfortably cold environmental temperatures, which can register 100 degrees or more below this homeostatic temperature in winter. On a warming planet, however, the hazard of extreme temperatures for human health is rapidly shifting toward the hot side of the comfort continuum – a condition for which we have fewer adaptive tools.

If your focus is on how the temperature and density of the atmosphere are influencing the operation of an aircraft, such as the length of runway that will be needed to achieve sufficient lift for takeoff, shade-based measurements of temperature are ideal, in that the receipt of direct solar radiation by the aircraft will not impact aerodynamic performance outside of its effects on air temperature. It is for this reason that virtually all airports measure air temperature in the shade, which is, by turn, the temperature reported in the local weather forecast – known technically as the *dry bulb temperature*.

If your focus is rather on human heat stress – particularly under conditions of direct solar exposure – it is critical that both air and radiant temperatures be measured, as both can raise core body temperatures. Wet bulb globe temperature measurements capture a more complete set of drivers of human heat stress by accounting for air temperature, radiant temperature, wind speed, and humidity, among other variables, that may not be routinely recorded at weather stations. Conceptually, wet bulb globe temperature assumes that a wet cloth has been wrapped around a thermometer and that the thermometer is then swung through the air in a circular motion and in full sunlight. This approach to wet bulb globe temperature measurement, which was the literal measurement technique prior to the development of electronic sensors, effectively measures what the air temperature would be if moisture was unlimited and evaporative cooling was maximized, which is the condition directly simulated by the incorporation of a wet cloth on a thermometer.

Wet bulb globe temperature provides a direct indicator of the temperature experienced by the human body mediated by our ability to release water to the surrounding air in the form of evaporated sweat. If relative humidity levels are high, little water will evaporate from the wet cloth around the thermometer, resulting in less cooling of the thermometer and a higher temperature. It is a metric that provides a single indicator of the environmental threshold beyond which humans cannot effectively cool themselves through perspiration, our body's most essential physiologic tool to maintain thermal homeostasis in hot weather. This threshold is generally recognized as 95°F wet bulb temperature, which is roughly equivalent to a dry bulb temperature of 110°F and a relative humidity of 50 percent [10].[1] Due to the inverse relationship between temperature and humidity during the day, it is rare to observe a relative humidity of 50 percent at temperatures above 100°F, rendering a wet bulb temperature of 95°F quite extreme.

The availability of a single quantitative threshold to reliably predict health outcomes in response to environmental conditions distinguishes extreme heat from other climate-related hazards. For example, there is no single number on the Saffir–Simpson Hurricane Wind Scale that is recognized as a definitive threshold for human fatalities. Deaths during hurricanes are dependent on a number of adaptive factors, ranging from the physical integrity of buildings to the willingness of residents to seek shelter. Likewise, there is no accepted wildfire class size, ranging from a relatively containable Class C fire to a geographically expansive Class G fire, that is understood to with certainty result in a loss of life. Prolonged exposures to wet bulb temperatures in excess of 95°F are indicative of certain heat illness and likely death because there is no adaptive measure one can take, beyond the availability of mechanical cooling, to arrest the onset of core body temperatures outside of a physiologically tolerable range. It is for this reason that a wet bulb temperature of 95°F is now recognized, across national militaries and the wider realm of climate science, as the threshold for human survivability [10].

Throughout the entirety of recorded human history, a combination of heat and humidity sufficiently high to yield a wet bulb temperature of 95°F was never measured until very recently and is unlikely to have occurred prior to the advent of thermometers. The deadliest heat waves to date, including the 2003 European and 2010 Russian heat waves, which in combination resulted in more than 100,000 deaths, both registered maximum wet bulb temperatures of about 83°F, with corresponding relative humidity values under 40 percent on the hottest days in each event [11]. In the United States, the highest wet bulb temperature values have been observed in the southeast and along the Eastern Seaboard, and these most commonly top out at 85°F. Even the most recent intense heat waves in hot and humid India and Pakistan have not crossed this survivability threshold, despite reaching dry bulb temperatures in excess of 120°F [2].

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[1] The survivability limit for humans is based on the "wet bulb" temperature, which is closely related to the wet bulb globe temperature measure. Wet bulb temperatures are lower than wet bulb globe temperature, as wet bulb temperatures do not account directly for radiant temperature, which is measured with a black globe thermometer. In the interest of simplicity, I use these two measures interchangeably. In practice, there is no consensus survivability threshold for wet bulb globe temperature. Widely adopted guidelines for national militaries and athletic associations generally designate 90°F wet bulb globe temperature as the safe limit for outdoor activities.

With temperature records falling regularly, and as we continue to venture into a climate unvisited by humans, many dates are significant. But some are more significant than others. In 1988, Dr. James Hansen, then the head of the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, would publicly and with a high degree of scientific certainty alert the US Congress to the mounting threat of a human-enhanced greenhouse effect, with his testimony and accompanying projections widely covered in the media. While the field of numerical climate modeling has continued to advance in the more than three decades since his testimony, Hansen's projections of how the planet would warm in response to continued and accelerating emissions of greenhouse gases were remarkably aligned with observations through the year 2020. As someone who turned eighteen the year of his testimony, this event carries particular weight, given that mine is the first generation to have knowledge of the unfolding ecological collapse throughout the entirely of its adult life – and the first to be unmoved by it.

The year 1998 would reveal for the first time the present-day potential for runaway climate change. While 1998 is no longer the hottest year ever measured, it represents the steepest year-over-year spike of the last 25 years, with a twelve-month increase in global temperatures of more than 30 percent relative to a long-term average and a two-year increase of more than 80 percent. The hottest year on record at the time of this writing is 2020 [12], but even the intervening twenty-two years separating these periods (1998–2020) would not produce an equivalent shift in global temperatures as experienced between 1996 and 1998, with the 2020 global temperature anomaly representing a 67 percent increase over 1998. The extremity of the heat that summer would spark massive wildfires not in arid California but in humid Florida, burning for three months and destroying more acreage than all but two of California's largest fires to date [13]. Worldwide, climate-related events in 1998 resulted in more than 32,000 fatalities and 300 million displaced from their homes. The estimated $89 billion in economic losses that year was 60 percent greater than the total economic losses from extreme weather events during the entirety of the 1980s [14]. From our vantage a quarter century beyond, the climate extremity of 1998 can be understood as the first impact of the iceberg upon the hull – the arcing flare of its mass and depth.

The year 2017 would bring not only the most destructive Atlantic hurricane season in global history but a statistical signpost as to how far down the climate change road we had progressed in the three decades since Hansen's testimony. With 17 named storms and 10 hurricanes, including Harvey, Irma, and Maria, the 2017 season resulted in more than 4,600 deaths in the US, almost $300 billion in property damages (exceeding the GDP of 171 countries), and

Figure 1.3 Interstate US-90 submerged in the aftermath of Hurricane Harvey, September 2017. Justin Sullivan/Getty Images.

widespread blackouts impacting more than 10 million residents, some of whom would lack power for almost a full year [15,16]. During Hurricane Harvey, a Category 4 storm, Houston, Texas would receive an excess of 60 inches of rain – more precipitation in twenty-four hours than typically falls in a full year (Figure 1.3). The quantity of rain deposited on Houston was found to be consistent with at least a 500-year storm – a flooding event so rare as to be expected to occur only once in the period between the discovery of the New World and today. Yet 500-year flood events in Houston are happening more frequently; in fact, 2017 was the third year in a row that Houston would experience a 500-year flooding event [17].

This simple fact merits restatement: Houston endured for three years running a storm event so rare as to be expected to occur only once in twenty human generations. In the planetary epoch of the last 12,000 years – the Holocene – the probability of a 500-year storm occurring over three successive years would have been 1 in 125,000,000. In the current age of climate instability – increasingly referred to as the Anthropocene – the probability of such an occurrence is unknown, but it is inarguably higher. The lesson to be inferred from 2017 is not the need for new statistics but that, in an unstable climate, such statistics carry little predictive power.

To this brief list of climate change milestones, we must now add 2015 – the year in which the survivability threshold for environmental temperature was effectively reached. While the event went largely unnoticed at the time, a wet bulb temperature of 94.3°F was recorded in Bandar-e Mahshahr, Iran during an intense heat wave in which daytime dry bulb temperatures hovered close to 110°F and nighttime temperatures almost never fell below 90°F for a full week [18]. What most distinguished the Bandar-e Mahshahr heat wave, however, was the humidity. Situated astride the northernmost shores of the Persian Gulf, the city of 160,000 is warmed by winds from the shallow ocean with sea surface temperatures approaching that of a geothermal pool. For the entirety of a week, relative humidity values at times exceeded 80 percent and rarely dipped below 50 percent, even in the extreme heat of the afternoons. No data on heat injuries or deaths were released by the Iranian government.

The maximum survivability threshold of 95°F is, of course, the most optimal threshold – the threshold for a healthy, fit, well-nourished, and hydrated human. As described by one author, this limit "applies to a person out of the sun, in gale-force winds, doused with water, wearing no clothing, and not working" [10]. In other words, 95°F wet bulb temperature is what it takes to strike down the most resilient of human beings under conditions of no exertion, no insulation in the form of clothing, and in response to mediating environmental conditions that would never be encountered outside of a tropical storm. Given the unlikelihood of these conditions, the effective survivability threshold temperature is much lower than 95°F. According to the US military, 90°F wet bulb globe temperature is the threshold beyond which soldiers should immediately seek refuge and access to cooler conditions [19].

From this military threshold, we can adopt a rule for the rest of us. Given that wet bulb temperatures are neither commonly measured today nor reported, we need a set of guidelines for operating in a climate changed world, one in which, for the first time in human history, environmental temperatures can be sufficiently extreme to induce heatstroke in the most healthy of individuals – children, young adults, the fittest of athletes – in a matter of hours. While a wet bulb temperature of 95°F remains rare, in many parts of the world – including the United States, Europe, and the whole of Asia – exceedances of 90°F are occurring with increasing frequency.

So, here's a general rule: **> 100°F** with **50%** relative humidity. If the dry bulb temperature and relative humidity values forecast for the day meet or exceed these thresholds, seek shelter and cooling as you would seek protection from a hurricane. These numbers have real killing power; we should heed them.

With the effective attainment of the heat survivability threshold in 2015, and the continued uptick in global temperatures, the map for human settlement is at this very moment shrinking. While millions of humans reside in cities now too hot for safe habitation, the capacity to do so – or, at least, our collective capacity to overlook its cost in wellness and lives – is rapidly diminishing. Combined with the rising seas, an expanding zone of intolerable heat and humidity is already upending regional economic and political systems ill-prepared for rapid environmental change driven by unmitigated emissions of greenhouse gases. In some zones, adaptation is possible; in others, it is not. And so, the global human footprint that has been spreading since our initial forays from Africa more than a million years ago is, perhaps for the first time, losing its purchase on long-settled territory. No person alive today will be untouched by this retreat.

Changing the Weather

With a few seconds remaining in the game, the University Alabama men's basketball team was trailing Mississippi State University by two points. Having just been fouled by a Mississippi State player, the Alabama team had possession of the ball and, if it could convert the two foul shots, would send the game into overtime. Although no one inside the arena knew it at the time, the stakes for these two shots were much greater than a come-from-behind victory by Alabama and advancement to a championship game. With a strengthening tornado moving rapidly toward the Georgia Dome arena in Atlanta, where the game was drawing to its conclusion, a failure to convert either of the two penalty shots would release tens of thousands of fans to the exits, exposing them to a violent weather event for which no public warning had been issued.

Despite their rapid movement and powerful winds, tornados generally can be forecast well before touching ground. Referred to as a tornado "watch" in the United States, such vortical weather systems manifest first as intense thunderstorms and then with cyclonic rotating air masses that can be captured on weather radar systems, leading to a publicly broadcast tornado warning. Among the many ingredients needed for tornado formation is a high level of atmospheric moisture, which was not the case in the Atlanta area on the evening of March 14, 2008 – a key reason that no tornado watch was in effect (Figure 1.4). However, an additional ingredient – a strong updraft of heat over the urbanized region of Atlanta – was in plentiful supply and would help fuel the formation of a powerful tornado as the Alabama team was successfully completing its penalty shots – extending the game into overtime and keeping the fans in their seats, even as sections of the dome exterior were ripped away from the building [20,21].

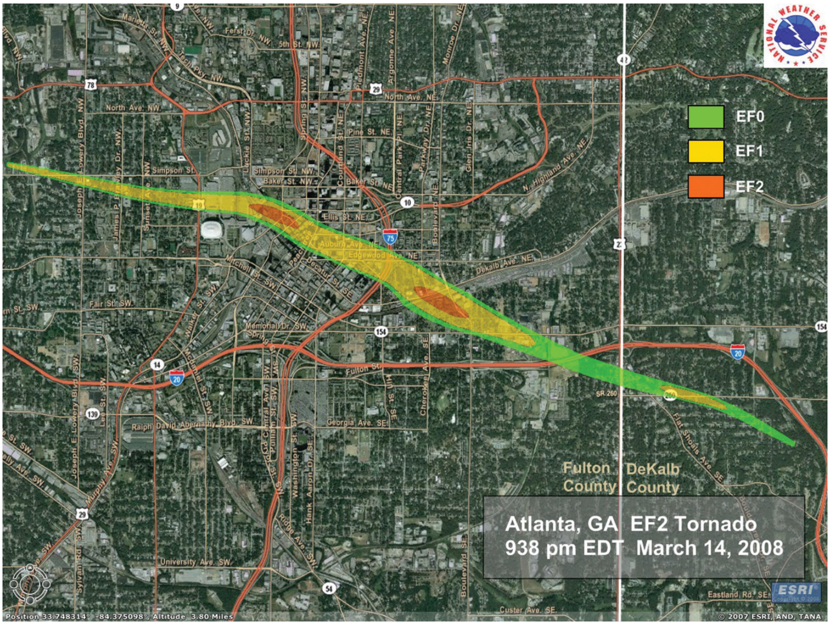

Figure 1.4 Path and intensity of a tornado in Atlanta, Georgia, March 14, 2008. US National Aeronautics and Space Administration, www.nasa.gov/topics/earth/features/atlanta_tornado.html.

It is often observed that no single extreme weather event can be attributed to climate change. Of all the technical caveats issued regularly by climate scientists, this is perhaps the most puzzling. All extreme weather events today are influenced to some degree by climate change, with a growing number attributable in full to higher baseline temperatures, higher baseline sea levels, and, in many regions, lower baseline levels of soil moisture. Given that sea levels are increasing every year, across the extent of the global oceans, a hurricane of historical intensity will generate a higher storm surge than in the past due to higher baseline water levels; all hurricanes moving forward are rendered more destructive as a product of higher sea levels. The same is true for the intensity, scope, and duration of heat waves.

Both global sea levels and temperatures are higher today than in the past due to human enhancement of the global greenhouse effect. Analogous to the glass panes of a greenhouse, gases naturally present in the Earth's atmosphere, such as carbon dioxide, absorb longwave radiation emitted from the Earth and are warmed by this radiation, elevating atmospheric temperatures higher than would be the case without these gases. The Moon, for example, has a much less dense atmosphere than the Earth (due to its low gravitational field) and lacks any measurable greenhouse effect, yielding temperatures too extreme for life. The Earth's natural greenhouse effect, in concert with the presence of liquid water and oxygen, is part of our ecological life-support system – we would not be here without it.

Human activity has not given rise to the global greenhouse effect, but our emissions increase the concentration of greenhouse gases naturally present in the atmosphere and, by turn, enhance planetary temperatures. This has long been true. During the period of the late Roman Empire, for example, the extensive burning of plant matter for fuel and metalworking released significant quantities of methane into the atmosphere, a potent greenhouse gas, likely contributing for a brief period to modestly higher global temperatures [22].

Since the dawning of the Industrial Revolution, both the quantities of greenhouse gases emitted from the burning of coal and the impact of these emissions on the planetary greenhouse effect have driven a clear and continuing rise in average global temperatures that reaches to the present moment. The retention of additional solar energy at the planetary level fuels more extreme weather through numerous drivers: the atmosphere carries more water for rainfall and the oceans, once warmed by the atmosphere, steadily rise through thermal expansion and polar melting. As described famously by Dr. James Hansen in his 1988 testimony to the US Congress, it is these human-enhanced emissions of greenhouse gases that have pushed the Earth outside of its long-established pattern of climate stability, resulting in a greater probability each year of weather events exceeding historical norms. Human activities have, as he described it, loaded the climate dice, with each roll now more likely to produce an outcome that was once rare.

This well-recounted climate change narrative has been extensively tested with both present observations and historical data – it is today, quite likely, the most exhaustively validated theory in the realm of the physical sciences. First proposed in the 1890s and supported with evidence every year since, the theory of a human-enhanced greenhouse effect has not been challenged in a scientifically meaningful way for almost half a century.

Importantly, however, a human-enhanced greenhouse effect does not explain the full extent of warming at the level of regions or, in particular, the level of cities. At physical scales generally less spatially expansive than that of continents, changes in the composition of the land surface can also drive temperatures higher than would occur in the absence of human activities. As noted in the Prologue, one such change is deforestation for agriculture or cattle grazing. As the extensive conversion of forest to grasslands reduces the quantity of rainfall that can be captured by forest ecosystems and retained as soil moisture, the resulting grassland ecosystems tend to be drier than the forest ecosystems that precede them, contributing to less evaporation from soils and plants, less rainfall, and, as a direct result, higher temperatures. This enhancement of temperatures as a product of regional land use change can serve to further amplify warming brought about through the emissions of greenhouse gases at the planetary scale, but the two warming mechanisms are physically distinct – one can occur without the other.

In cities, the conversion of forested areas, crops, or wetlands into buildings, streets, and parking lots also produces a warming effect. Referred to as the "urban heat island effect," late afternoon temperatures in cities are measured to be anywhere from 2°F to 20°F higher than proximate rural areas, yielding a magnitude of warming that is typically greater than that brought about through the global greenhouse effect [23]. The urban heat island effect is driven by four specific changes in cities. First, the removal of forest cover and other green plants reduces both shading and the rate at which water is returned to the atmosphere via evaporation and transpiration, processes that cool the urban environment akin to the cooling of skin through perspiration. Much like a forest converted to a grassland, the resulting degradation in photosynthetic activity and vegetative biomass from land clearance will bring about in most regions of the planet a warming effect, even prior to the development of the city itself.

Second, the introduction of impervious construction materials to the cleared landscape, including concrete, asphalt, and roofing materials, greatly enhances the "thermal capacity" of the resulting built environment, or the quantity of heat energy that can be stored by these materials and released back to the atmosphere, elevating temperatures. The extensive use of paving and roofing materials in cities also serves to waterproof large swaths of the urban environment, limiting the infiltration of rainwater into urban soils and reducing average soil moisture. The process of urbanization, in this respect, is effectively a process of desertification, yielding a climate much drier and hotter than that displaced by the footprint of the city.

Having transformed the landscape into a more efficient machine for the absorption, storage, and reemission of heat energy than the natural land covers that are displaced, the largest cities further compound their warming effect through the creation of large urban canyons. Constructed through the clustering of tall buildings or the introduction of walled roadways below grade (or both), the prevalence of vertical surfaces in cities, fashioned from stone, concrete, and glass, traps outgoing longwave radiation much like the radiative trapping of greenhouse gases. Impeded from escaping the urban canyon, some fraction of outgoing radiant energy is reabsorbed and reemitted by building walls, further elevating their temperature and enhancing the urban heat island effect.

A final mechanism through which cities elevate their own temperatures results from the extensive use of energy – most of it derived from fossil fuels – to generate electricity and power mechanical processes. Governed by the second law of thermodynamics, some fraction of the energy used to carry out mechanical or electrical work – whether in the form of a vehicle engine, an industrial press, or an illuminated light bulb – will be transformed into waste heat energy and emitted from tailpipes, smokestacks, or radiated directly into the ambient air. This waste heat energy is sufficiently concentrated in cities to elevate air temperatures and further enhance the urban heat island effect. In this sense, cities are heated by solar energy from two eras: present-day sunlight that is more efficiently captured and stored by urban materials than by the natural landscape and ancient sunlight, captured by green plants eons ago and embalmed as fossil sources of energy. It is this compounding of solar energy – the present augmented with the ancient – that renders large cities among the most extreme environments found today on Earth.

In combination, these four drivers of the urban heat island effect – the removal of natural land covers, the introduction of materials with a high thermal capacity, the creation of urban canyons, and the release of copious quantities of waste heat energy – not only change the climate of urbanized regions over time; these characteristics of cities change the weather. If climate is the long-term pattern of weather experienced across a region and weather events are short-term, day-to-day meteorological phenomena, cities have been clearly demonstrated to have a pronounced effect on both temporal scales – ranging from the thirty-year average temperature to the intensity of a multiday heat wave to the instantaneous wind speeds of a tornado. This unique characteristic of urban areas – a tendency to amplify the solar receipt of energy – is rapidly accelerating the pace of climate change in cities.

Occupying less than 2 percent of the global land surface but home to more than half of the global population, cities today are simultaneously the most climatically hazardous and commonly chosen pattern of human settlement. Residents of cities experience the same intensity of greenhouse-induced warming as found outside of urban areas and compound these heat exposures with the even greater thermal liability of the urban heat island effect. Data collected over a fifty-year period in and outside of the largest cities across the United States find the majority to be warming at about double the rate of the planet as a whole, with the urban heat island effect responsible for more than half of this warming year-over-year [24]. As a result, every observable dimension of heat waves in cities – including the frequency, intensity, duration, and seasonality – is increasing and, in most instances, increasing rapidly [25]. To live in the center of a large US city today is to confront a risk of heat morality 200 percent greater than for those living on the urban fringe, where heat islands are less pronounced [26]. If a human-enhanced global greenhouse effect has loaded the climate dice, in cities we are playing the game with more than two dice – and still throwing for doubles.

But cities, to a much greater extent than rural areas, can alter their climate odds. Rendered by decades of development more absorbent of solar energy, less capable of cooling through an exchange of moisture between the land surface and atmosphere, and far more generative of their own fossil heat emissions, cities can be physically redesigned to moderate these warming effects and, in some instances, exhibit temperatures lower than their predevelopment landscapes. Cities can and should be places of less heat and carbon-intensive modes of travel than nonurban settings. Cities can be modified to capture and store more rainwater than is lost through extensive surface sealing, recharging soil moisture, bolstering drinking water supplies, and leveraging water stores for direct cooling when climatically advantageous. Cities can be made once again, as they were prior to their industrial remaking, responsive to their local climates, and adherent to their ecologically delimited carrying capacity. Cities can, in short, shape their climate fate.

In the remainder of this chapter, I will consider four specific classes of urban design strategies – referred to collectively as *urban heat management* – available to cities to significantly moderate both the pace and the extremity of urban warming. The design and materials-based strategies considered range from the ancient to the experimental and are not uniformly suitable for every urban setting. While these strategies provide a physical toolkit for moderating the extremities of heat in cities, they address only one dimension of a broader approach to managing heat risk. Equally important are emergency response protocols that can be activated during periods of extreme heat – such as early warning systems for heat waves and the provision of cooling centers – as well as the enhancement of individual adaptive capacity, including well-insulated housing and access to transportation for evacuation, when warranted. While these latter topics are not the focus of the following discussion, they remain critical elements of climate resilience plans and should be implemented in concert with physical changes to the built environment of cities.

While each of the strategies to be considered has been implemented in some combination and at some scale by the most forward-looking municipal governments, no city to date, in any reach of the planet, has undertaken the physical transformation of its built environment needed to safeguard its population from the coming heat. With the typical municipal budget allocation for heat management still falling short of monies appropriated for the annual patching of potholes, no city to date has embarked upon the almost complete resurfacing of the built environment – including every road, every parking lot, and most every roofing surface – that will need to be programmed in the present decade. If the resulting greening and lightening and watering of the urban environment is ancient in its conception, it must be radical in its implementation to maintain the viability of cities in a climate changed world. Nothing less will meet the moment.

Greening

July 21, 2019, was a hot day in Cambridge, Massachusetts – the hottest of the summer. With typical July temperatures in this small city within the larger Boston area reaching to only 85°F, temperatures exceeding 100°F – as reached on that day – are rare, and these extremes are not experienced in all neighborhoods. East Cambridge is a neighborhood characterized by dense, low-rise housing, narrow streets with limited tree cover, and much less park space than other Cambridge neighborhoods. With little tree cover available for the shading of streets or cooling through transpiration, East Cambridge is often more than 10°F hotter than other areas of the city, and it is also the neighborhood in which the fewest residents have access to air conditioning. In light of the elevated heat risk confronted by residents, a colleague and I were invited by the city to carry out a sort of do-over for July 21. If we go back in time and remake East Cambridge to be more heat adaptive, to what extent could extreme summer temperatures be lowered? To what extent could hospital visits and heat-related deaths be reduced?

The do-over for July 21, and every day during the summer of 2019, would take the form of a climate model simulation. Despite the grave risk posed by extreme temperatures in cities today, few cities invest much effort in monitoring this risk. The truth is we have no direct means of knowing what the temperature was in East Cambridge on July 21, 2019. The most proximate permanent weather station to this neighborhood is at Boston's Logan Airport, a few miles to the east and situated at the mouth of Boston Harbor – a very different climatic setting than a dense residential neighborhood only partially bounded by water. While there are security cameras positioned at numerous locations across Cambridge, by comparison there are very few temperature sensors for which historical data are available, and none of these is located in the neighborhood confronting the greatest heat risk. Driven by extensive information on the physical characteristics of every city block in Cambridge – every building, rooftop, roadway, greenspace, and tree – combined with regional weather patterns for every hour of the day, urban scale climate models provide a highly reliable tool for simulating weather where we lack direct observations. Such climate models allow us not only to travel in time, reproducing historical weather conditions, but to simulate how the weather on a particular city block would change in response to alterations in the immediate physical environment, such as the addition of trees or reflective roofing materials.

Prior studies focused on how a greening of cities could lessen their heat risk have shown a great potential for a restoration of natural land covers, where annual rainfall is sufficient, to substantially cool the urban environment. In what now numbers in the thousands of technical studies – some dating to the 1960s and supported with data from cities situated across every populated continent – the literature on *urban heat management*, a subfield of urban climatology focused on cooling cities through a more climate-responsive physical design, is definitive: green plants in urban environments lessen the extremity of heat, often dramatically [27]. This lessening of heat scales with the horizontal extent and vertical density of green cover, carries no significant cooling penalty in the winter months, and is highly compatible with other aims of climate change adaptation, such as flood control. The cost of increasing and maintaining green cover in cities is not insignificant but is more than offset by the avoided energy costs associated with lower summer temperatures [28]. And the greening of private property enhances its value, yielding an economic return to landowners, as well as to city governments in the form of increased property taxes [29]. Among all of the grim headlines associated with climate change, this simple observation tacks differently: *We can make our cities more resilient by making them more beautiful*.

The extent of cooling provided by tree canopy has been found to be relatively consistent across different climate types. Our heat assessment work in Cambridge and other cities finds that the shading of 1 percent of a neighborhood’s area with tree canopy lessens late afternoon temperatures by about 0.2°F. This rate of cooling has been found to be roughly consistent across cities located in cool and humid settings, such as Cambridge, and those located in hot and arid conditions and is drawn from studies focused on cities with an average tree canopy cover of between 10 percent and 40 percent [28,30,31,32]. For reference, the average tree canopy cover for a sample of large US cities was found to be around 30 percent [33]. In these cities, as a general rule of thumb, an increase in neighborhood-wide tree canopy of 10 percent, if well distributed, can be expected to lower temperatures by about 2°F. This is a substantial level of cooling and, in many large cities, is on par with the level of additional warming projected to occur by mid-century, enabling some or all of this anticipated warming to be offset [31,32]. But cities should aim much higher than for a 10 percent bump in tree canopy.

What extent of citywide tree canopy is possible? This question is of less direct import than the relative canopy cover of residential areas and zones with significant pedestrian activity. In these zones, a minimum canopy coverage of 40 percent has been observed to yield the greatest increase in cooling per tree added [34]. But this is a minimum – residential districts of many large cities would be well served by a canopy coverage of between 40 percent and 60 percent, representing in many North American cities a doubling of average citywide tree canopy.

To understand if such an extent of tree canopy is feasible, we must only look to contemporary examples. Returning to Cambridge, a dense city by US standards, about 30 percent of the city is presently overlaid with tree canopy. According to the US Forest Service, if we account for areas available for planting, including non-road impervious areas, such as parking lots, 65 percent of Cambridge could be overlaid with tree canopy [35]. Applying the same Forest Service methodology, a similar canopy potential exists in New York City (64 percent), with 50 percent of Manhattan found to be capable of supporting tree canopy based on present-day development patterns [36]. Similar numbers are found across the Eastern United States – 67 percent of Washington, DC is plantable [37]; 69 percent of Philadelphia [38]; 71 percent of Baltimore [39]. While somewhat less green than eastern cities, many cities of the western US can support tree canopies in excess of 40 percent, such as Boise (57 percent) [40], Portland (52 percent) [41], and semi-arid Sacramento (45 percent) [42]. The vast majority of the US population lives in cities where a much more extensive canopy of tree cover is feasible with no change in present-day development patterns and allowing for future population growth (Figure 1.5).

A substantial increase in tree canopy is not delimited by suitable land or rainfall patterns in most cities, but it is delimited by an insufficient allocation of resources. How much would it cost to increase the tree canopy from 30 percent to 50 percent in a dense city like Cambridge?

An analysis of thirty-four studies drawn from around the world (with the majority in North America) finds the average annual cost of urban tree planting and maintenance to be about $38 per tree [43]. More recent work focused on the annual cost and maintenance of street tree planting and maintenance in California cities finds this cost per tree to be about $110 [44]. As the planting of trees along streets and in proximity to other types of impervious cover carries the greatest cooling potential, a rounded estimate of $100 per tree per year – closer to the cost tallied for street trees in California cities – provides a reasonable basis to understand

Figure 1.5 Street tree canopy in Brooklyn Heights, New York. Ellen Isaacs/Alamy Stock Photo.

the budgetary implications of increasing the average citywide tree canopy in most regions of the planet. Based on our work in Cambridge, an additional 60,000 trees would be needed to attain an average canopy cover of 50 percent in every neighborhood. Assuming a conservative annual cost of $100 per tree (as not all newly planted trees are assumed to be street trees), the additional annual cost to Cambridge of undertaking this tree planting and maintenance program would be $6 million, representing less than 1 percent of the current annual budget, about 4 percent of the annual budget for policing services, or an approximate doubling of the current budget allocation for urban forestry [45].

In outlining these cost comparisons, my intent is not to trivialize an additional annual expense of $6 million to a modest-sized US city. It is to highlight that the costs of expanding the urban forest, even in the most dense of urban environments, are consistent with other annual expenditures on critical urban services and infrastructure. The costs of expanded tree planting and maintenance in Cambridge represent less than a quarter of the annual cost of servicing bonds issued for the construction and maintenance of sewers [45]. Cambridge need not conclude that trees are more important than storm sewers in a climate changed world, but the city's leaders must recognize, perhaps for the first time, that urban heat management is equal in importance to public welfare as flood management.

An additional point to make on the flooding versus heat management comparison is that we have no technological analog to engineered sewer systems for lessening heat exposure in cities. As urban populations confront for the first time an intensity of heat that will not permit even the most healthy of individuals to work a full day outside, or typical summer temperatures that render little league baseball unsafe, the development of a technology capable of measurably cooling cities through a partial blocking of solar radiation and a phase change in water – and one that could do so at a cost representing less than 1 percent of the annual city budget – would be considered a miracle of innovation. Were an engineered solution available for ambient cooling in cities – such as the sidewalk air conditioning of Doha – it would undoubtedly require a tremendous investment of material and energy and would carry a significant carbon footprint. Tree planting, by contrast, requires no research and development, produces no ambient noise (or waste heat emissions), and would have a net effect of reducing rather than increasing atmospheric carbon dioxide. What we have in the form of trees is a climate management tool surpassing the performance of any that humans could hope to create – and one that, amazingly, would soon dominate the landscape again in most cities if we simply stopped suppressing their growth.

The hottest day of the Cambridge summer in 2019 would have been remarkably less hot were at least 50 percent of every neighborhood in the city overlaid with tree canopy. In East Cambridge, the neighborhood found to exhibit the highest late afternoon temperatures across the summer, the high temperature that day would have been 6°F cooler – sufficient to more than offset the projected magnitude of warming by mid-century and possibly end of century. For the summer as a whole, the number of hospital visits for heat-related illness in East Cambridge would have been about 25 percent lower, and the number of heat-related deaths almost 50 percent lower. Through tree planting alone, Cambridge can effectively hold the line on heat for another generation – an outcome that no greenhouse gas emissions control technology or program, no matter how aggressive, could feasibly achieve.

If there is anything radical about the proposal to increase urban tree canopy in large cities to 40 percent or 50 percent or even 60 percent, and to do so in the most densely developed areas, it is only in the required expansion of our conventional thinking about infrastructure. Cities allocate tens of millions of dollars every year to the construction and maintenance of sewer systems and road systems and water delivery systems because these systems are fundamental to the viability of urban life. In a climate changed world, the expansion and maintenance of dense tree canopy are no less fundamental to the viability of cities. If we can put rovers on Mars, we can put trees in dense street corridors, throughout parking lots, and even atop buildings (Figure 1.6). This is not

Figure 1.6 Trees incorporated into building rooftop and terraces, Vancouver, Canada. JSM Images/Alamy Stock Photo.

a technical feat beyond our capacity or our budget, but it cannot be achieved with a mindset that urban trees are principally ornamentation.

Reaching these canopy targets will require the engineering of planting spaces to support healthy root growth, the monitoring of all public trees for regular maintenance of health, and a well-calibrated nursery program to rapidly replace trees when lost to extreme weather, pests, and other causes of canopy loss [46].[2] None of these requirements render an expansive urban forest less feasible than other types of urban infrastructure, and none would place undue stress on municipal budgets. For slowing the rise of temperatures in all but the most arid cities, trees are the most basic of a new class of adaptation infrastructure – the surest arrow in the resilience quiver.

Shading

With urban tree canopies in decline in most large cities of North America [33], one land use category is experiencing a quiet revolution in adaptation planning for heat: the playground. The focus of now long-standing public

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[2] The New York City Parks Department, for example, has created an online map displaying the location of its 692,892 trees planted across the city, including the maintenance history for each as well as a running tally of climate benefits (see [46]).

health campaigns undertaken by the US Centers for Disease Control and Prevention and the Trust for Public Land, a nongovernmental organization focused on greenspace development and design, a significant number of playgrounds have increased tree canopy or installed shade structures to lessen solar exposure among children [47,48,49]. Initially designed as a response to a rising epidemic of skin cancer, artificial shade structures in playgrounds and other athletic facilities are the leading edge of a trend toward the greater shading of urban environments as an adaptive response to rising temperatures. While less effective in lowering ambient temperatures than tree canopy, shade structures nonetheless yield substantial cooling benefits and can be deployed over spaces inhospitable to tree canopy. A long-standing feature of urban design in hot and arid climates of the Middle East and Mediterranean basin, urban shade structures are being deployed over entire street corridors to reduce the duration of intolerable heat exposures in commercial areas. The extensive integration of natural and artificial shade in large cities stands as a promising but largely untested adaptation strategy in other regions of the world.

The effectiveness of shade structures in lessening human heat stress is well established by hundreds of studies spanning all major climates of the globe. Importantly, the provision of shade by such structures – including covered transit stops, pergolas over walkways, mesh screens, fabric canopies, and a wide range of materials, both modern and ancient in construction – is found to significantly reduce heat stress without substantially reducing air temperatures. Shade structures moderate heat stress through the attenuation or complete blockage of incoming solar radiation, which often has the effect of lowering radiant temperatures without significantly lowering air temperatures. As noted, the physiologic effect of radiant temperature is experienced when moving from direct sun to complete shade on a hot day. Given that environmental heat is transferred to the human body via the direct receipt of solar radiation and via convection from the air that surrounds our bodies, the moderation of either source of heat energy will lessen heat stress. While the blockage of radiant energy by shade structures does have the effect of lowering the temperature of the air under the structure, the relatively small fraction of the urban environment shaded by such structures does not yield much of a cooling effect on the extensive volume of the urban airshed. But these structures do cool our bodies measurably while we remain within the shade they cast.

Here, again, the extent to which dry bulb air temperature – the environmental variable most commonly reported by weather stations – fails to directly account for the effects of other environmental variables on heat stress, including the direct receipt of solar radiation and humidity, militates for the use of more direct measures of heat stress, such as wet bulb globe temperatures. To understand the potential role of shade structures in lessening human heat stress, a study in hot and arid Phoenix, Arizona measured a full set of heat exposure variables in the shade of trees and artificial shade structures within an urban park. While the maximum dry bulb temperature on a summer afternoon reached 104°F, a more complete index of heat stress found temperatures to be equivalent to 124°F in full sun. Moving into the shade of trees within the park was found to lower the heat stress index by more than 20 degrees, to 101°F – still hot but less life-threatening in the arid climate of Phoenix. The cooling effect of shade structures was found to be about 80 percent that of tree canopy, lowering the heat stress index to about 105°F [50].

Both the extent to which shade can lessen heat stress and the relative cooling effectiveness of natural and artificial shade have been found to be largely consistent in studies sited in desert, subtropical, and tropical climates. Studies focused on pedestrian zones in Colombo, Sri Lanka, Nagoya, Japan, and Rome, Italy, for example, find the provision of shade from adjacent buildings or other structures to lessen a heat stress index by between 20 percent and 30 percent – a bit higher than the range found in Phoenix [51,52,53]. Studies comparing the relative effectiveness of natural and artificial shading find shade structures to yield at least 80 percent of the cooling effect of tree canopy [50,51,54], demonstrating the utility of artificial shade for managing heat stress in lieu of or in concert with tree canopy.

For cities confronting a rise in heat exposures beyond the range of human tolerance, the development of extensive and interconnecting shade corridors will be required to sustain pedestrian activity and support critical infrastructure for emissions reduction programs, such as the wider use of transit systems (Figure 1.7). Fabricated shade structures, in particular, provide a climate management strategy supportive of moderating the impacts of climate change in cities while simultaneously lessening carbon emissions – a set of strategies I refer to as *adaptive mitigation* [23]. Already deployed in some cities as scaffolding for solar photovoltaic (PV) systems positioned over parking lots, the integration of shade structures with micro-grids – decentralized renewable energy systems capable of supplying power to the grid when centralized power stations and transmissions systems are disabled by extreme weather or other causes – is a low-hanging strategy that enhances resilience while lowering greenhouse emissions. The development of shade structure systems to the extent required in many cities will simultaneously create a new layer of urban surfaces ideally positioned for the deployment of solar PV

Figure 1.7 Shade structure over street in Granada, Spain. Benedek/iStock.

collection cells across dense urban corridors, precisely where the demand for renewable energy is greatest.

Fabricated shade structures provide an essential heat adaptation strategy in highly trafficked zones of cities situated in climates too arid to support extensive tree canopy. As urban populations are exposed to extreme temperatures not only during episodic heat wave periods but increasingly throughout long stretches of the summer months, heavily shaded, “cool corridors” will need to be fashioned from both natural and fabricated shade structures across entire urban districts. In cities with rainfall patterns supportive of tree growth, the integration of fabricated shade structures with trees may provide opportunities for enhancing the resilience of urban trees to storm damage from the physical tethering of trunks to permanent shade structures. A long-practiced defense against wind damage in hurricane-prone regions, trees in fruit orchards are often stabilized with support systems including guying straps or wires and root ball anchors [55]. The use of permanent shade structures as tree support systems, in concert with the selection of tree species most resilient to wind and drought, provides an opportunity to both lengthen the reach of such corridors across urban districts and extend the life of valuable green infrastructure.

Reflecting

As we ascend ever further up the climate change mountain, a proposal to slow the rate of planetary warming through geoengineering – a set of Hail Mary strategies to cool the planet through untested, global-scale efforts to, for example, inject aerosols into the upper atmosphere or seed the global oceans with nutrients to increase the rate at which carbon dioxide is absorbed – is being actively debated by climate scientists. The risk of these approaches is not only in their unknown secondary effects (like an unanticipated disruption in global agriculture) but also in the necessary scale at which such approaches must be implemented. Experimentation with planetary physics risks irreversible changes, but the same is not true for urban-scale geoengineering. Beyond the restoration of natural land cover, such as tree canopy, cities can also be physically modified to reflect away incoming solar radiation, producing a localized cooling effect. A technique long practiced in premodern white-washed villages of the Mediterranean, where the extensive use of white paint and naturally reflective building materials lessen the quantity of energy absorbed from the Sun, new classes of engineered materials are capable of cooling buildings to such an extent that air conditioning may not be needed except on the hottest days.

Enhancing the reflectivity of surface materials cools the air by short-circuiting the usual pathway through which sunlight warms the Earth. With a limited number of exceptions, the communities of plants and animals that comprise the Earth's biosphere have evolved to absorb solar energy – often as much as can be gathered across a small surface area. The dark green hue of an oak tree leaf, as one common example, assists the tree in retaining much of the solar energy that falls upon it, driving, in turn, photosynthesis and the set of biological functions carried out by the living tissue of the tree. Lighter-hued materials, by contrast, such as fresh snow, reflect away more incident solar radiation than is absorbed, a property that slows the rate at which snow will melt on a clear day. Evidence of this strong reflective property of snow is manifest in the sunburned faces of unprepared skiers, an outcome of the upward flux of solar energy reflected from the snowpack.

The reflection of sunlight away from the Earth's surface cools the air by lessening the quantity of heat energy absorbed and reemitted from the ground. Governed by the same properties that drive the global greenhouse effect, reflected solar radiation is permitted to pass back through the atmosphere, without warming the air, because this radiation has not been transformed into longwave, infrared radiation – the form of radiation absorbed by greenhouse gases. Shortwave radiation (mostly visible light) is transformed into longwave radiation (mostly infrared, thermal radiation) when absorbed by surface materials and reemitted at a lower temperature and (by physical law) a *longer* wavelength than the visible radiation received from the Sun. Like a mirror that reflects your image back at you, highly reflective surface materials simply return shortwave, solar radiation to the atmosphere without converting it into longwave radiation.

Knowledge of these physical properties of radiant energy enables a reengineering of cities to be less absorbent of solar energy through the use of more reflective building materials in new construction or the application of reflective coatings to existing buildings. Measured on a scale from 0 to 1 and referred to in technical parlance as "albedo," the reflectivity of cities can be increased through the use of lighter-hued roofing and paving materials, such as a white surface coating on the flat roof of an industrial building.[3] To assess the extent to which high albedo roofing and paving materials could lower temperatures on a hot summer afternoon, we modeled such a scenario for the same recent summer period in Cambridge, Massachusetts for which we measured the benefits of planting more trees. In doing so, we assumed a greater increase in the reflectivity of rooftops than for surface paving in the form of streets and parking lots, as the use of high albedo materials at ground level can create glare. While a high level of solar reflection at the level of rooftops is less of a concern for visibility, too much reflection at the street level can be hazardous for drivers and cyclists. With this in mind, we assumed all of the streets of Cambridge were converted from darkly hued asphalt paving to more lightly hued concrete and that all rooftops were converted to levels associated with commercially available "cool" roofing materials, depending on whether the building had a flat (more reflective) or pitched (less reflective) roof.

Our modeled "do-over" for the hottest day of the summer in 2019 finds that reengineering the city to be more reflective would lower temperatures by between about 0.5°F to 1°F in the late afternoon, depending on the neighborhood. This variability in cooling benefits is largely driven by the surface area available in each neighborhood for cool materials – in higher density neighborhoods with more roofing area, the benefits of reflective roofing are greater. Overall, each 10 percentage point increase in albedo was associated with about

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[3] It should be noted that conventional "cool materials" used for roofing and paving applications are also engineered to exhibit a high "emissivity," in concert with a high albedo. Thermal *emissivity* is a property of materials measuring the rate at which absorbed solar energy is returned to the atmosphere. Materials with a high emissivity (also measured on a scale from 0 to 1) are able to release heat energy back to the atmosphere efficiently and quickly, which limits the quantity of heat energy retained by the material. By storing greater quantities of energy received from the Sun, lower emissivity materials will experience a greater rise in temperature than higher emissivity materials, assuming all other thermal properties are held constant.

0.5°F of cooling at the neighborhood level – suggesting that a 20 percent increase in roofing and paving reflectivity, an obtainable goal in Cambridge, could lessen late afternoon summer temperatures by about 1°F. This rate of cooling compares well with numerous other studies focused on cool materials, which tend to range from roughly 0.5°F to 1°F of cooling with each 10 percent increase in surface albedo and average about 0.7°F [56]. Based on our modeling work in Cambridge and other cities, a greater use of cool materials for roofing and paving materials is roughly 25–50 percent as effective as tree canopy in lowering neighborhood-scale temperatures during the summer, assuming the same land area is converted to either treatment.

A second thermal property of urban construction that can be engineered for greater cooling is the capacity for phase changes to moderate peak temperatures. Similar to the effects of a phase change in water-to-water vapor, a phase change in building materials from a solid to a liquid phase can alter the timing at which solar energy absorbed by a building is returned to the atmosphere in the form of heat. The encasement of paraffin (wax-based) capsules in the voids of exterior walls, for example, enables a greater percentage of the energy absorbed during the day to be stored by the building wall, as the solid paraffin converts to a liquid through melting, without contributing to higher temperatures. At night, once the air temperature cools, the stored heat energy will be slowly released as the paraffin material undergoes a reverse phase change back into a solid. The use of phase change materials in roofing tiles has been found to outperform high albedo materials by about 30 percent, suggesting the potential for a combination of high albedo and phase change materials to lessen air temperatures more significantly than conventional cool materials alone [57].

Recent advances in super-cool coatings for building roofs suggest the potential for cool roofing materials not only to reduce the quantity of heat emitted by urban structures but to measurably cool the surrounding ambient air [58]. Derived from the pigmentation of white paint with barium sulfate nanoparticles, the resulting “ultra-white” coating has very high levels of material albedo (0.98) and emissivity (0.96), serving to reflect away almost all intercepted solar energy. While conventional cool materials lessen the quantity of heat returned to the atmosphere relative to traditional roofing materials, such super-cool materials can exhibit a surface temperature that is actually lower than that of the overlying atmosphere, serving to reduce the temperature of the air much like an outdoor air conditioning system and transmitting no thermal energy into the building itself. The demonstrated cooling effect is so great that the use of these materials for single-story structures could eliminate the need for mechanical air conditioning inside the buildings on most days, easily offsetting the additional cost of incorporating these coatings into roofing materials.

Importantly, the potential for this new class of ultra-white cool roofing materials to remain highly reflective over time in response to weathering is not yet demonstrated. Nonetheless, a growing emphasis on such adaptive mitigation strategies for cities – those designed to reduce the drivers (greenhouse gas emissions) and impacts (extreme heat) of climate change simultaneously – is yielding scientific advances that could substantially cool cities through a scale of geoengineering far less likely to carry irreversible side effects than planetary-scale interventions. If combined with other heat management strategies better suited to pedestrian environments, such as tree planting, it is not beyond our reach to substantially lower temperatures in cities and to offset, in turn, many decades of warming brought about through the global greenhouse effect.

Watering

First measured in nineteenth-century London, the long-lived and growing intensity of the urban heat island effect – perhaps the first scientifically documented evidence of human-driven climate change – may begin to abate in some of the world's largest cities over the coming decades. In what would represent the first substantial federal investment in climate change adaptation for heat in the United States, the Infrastructure Investment and Jobs Act of 2021 allocated hundreds of millions of dollars for the expansion of green infrastructure and cool materials in urban areas. As the performance of thermally engineered building materials continues to advance, coupled with an expansion of tree canopy and shade structures in response to more extreme heat events, urban heat management carries the potential to render cities cooler than surrounding rural areas. The potential for such "urban cool islands" is growing as freshwater supplies are declining in agricultural areas around cities. Outside of monsoon periods in India, for example, a significant number of cities exhibit lower temperatures during the day than do nearby rural areas characterized by extreme drought conditions and little vegetation [59]. A related outcome in agricultural areas confronting dwindling groundwater supplies is the likelihood of more intense heat waves with a reduction in regional rates of cropland irrigation [60].

A growing extremity of temperatures in rural areas with a shift toward drier conditions attests to the power of a single environmental variable in regulating air temperatures: water. If the release of water by green plants through transpiration is a dominant driver of air temperatures, to what extent could the irrigation of urban greenspace and streets offset temperatures during heat wave conditions? To what extent would urban irrigation elevate heat risk through the enhancement of humidity and wet bulb temperatures? While there is not today an extensive scientific literature focused on these questions, the available evidence suggests that urban irrigation – where water supplies can support it – can measurably lower heat exposures in cities, even when accounting for a modest rise in humidity. A recent review of studies assessing the potential for enhanced irrigation to lower afternoon temperatures in cities finds modeled day and nighttime temperature reductions to range from about 1°F to 10°F, with no study finding evidence of an increase in temperatures [61]. The greatest potential for reducing temperatures through a more extensive watering of urban vegetation is found in hot and dry cities, such as Phoenix or Las Vegas, where humidity levels are typically low. A common finding of these studies is that increasing levels of urban irrigation (or water availability) are associated with decreasing cooling benefits, suggesting that this strategy carries more limited benefits for cities in humid climates.

To be viable in arid cities, where freshwater supplies are already stressed, reclaimed sources of non-potable water would be needed. In cities constructing *sustainable urban drainage systems* (SUDS), a set of techniques through which stormwater and greywater (recycled domestic wastewater free of fecal contamination) are captured and stored for reuse, the irrigation of urban vegetation may provide a suitable use of these reclaimed water supplies. To assess the potential benefits of urban irrigation for heat management in Adelaide, Australia – a city with expanding greywater infrastructure – a recent study modeled the effects of the irrigation of urban greenspace (with no increase in the total area of urban vegetation) on temperatures during heat wave conditions. The results found average daytime temperatures fell by more than 4°F during an intense heat wave, with maximum temperatures falling by more than 15°F in zones with high soil moisture levels, suggesting a strong potential to deploy watering as an emergency response strategy during heat wave conditions. A heat index, accounting for the combined effects of temperature and humidity, was also found to fall in response to widespread urban irrigation during heat wave conditions – during both the day and the night [62].

A decade after what remains among the deadliest weather disasters on record – the European heat wave of 2003 – French researchers carried out experiments focused on street watering during conditions of extreme heat in the cities of Paris and Lyon. In each experiment, surface and air temperatures were

Figure 1.8 Street watering during heat wave in Moscow, Russia, July 2021. Alexander Sayganov/SOPA Images/LightRocket via Getty Images.

measured across adjacent portions of the same urban street, with one block sprayed by watering trucks with greywater at regular intervals and the adjacent block left untreated. An earlier study used a climate model to estimate the benefits of street watering citywide during heat wave conditions. The results demonstrated a modest cooling effect at the scale of the single street corridor, with a maximum air temperature reduction of about 1.5°F, and a potentially greater effect from citywide street watering, estimated at up to 3.5°F [63]. Reflecting the need to account for both the temperature and the humidity effects of street watering, wet bulb temperature effects were measured during a similar experiment in Lyon, finding a maximum reduction of about 1°F in this most direct indicator of heat stress [64].

Performed in cities with high levels of summer humidity, these experimental studies in Paris and Lyon, combined with modeling studies focused on greenspace irrigation in hot and arid climates, support the deployment of urban irrigation as a strategy to moderate temperatures during heat wave conditions (Figure 1.8). While the cooling effects estimated from irrigation do not match those achievable through enhancements in tree canopy, a key advantage of irrigation is the potential to deploy it as an emergency response strategy during dangerously hot weather with existing resources, such as watering trucks, and with no needed change to the built environment of cities. While the development of greywater collection and storage systems is needed to enable such an approach in arid regions, many large cities confronting growing water scarcity are already investing in integrated water management systems for a wide range of water needs.

The demonstrated cooling benefits of the various heat management strategies considered in this chapter suggest the potential to combine techniques to maximize temperature reductions during summer conditions. To date, a large number of modeling studies has been carried out focused on the combined effects of urban vegetation and cool materials. The median modeled cooling benefits of these now commonly adopted strategies, across a diversity of countries and climate types, is found to be about 3.5°F – a level of cooling associated with a wide range of assumptions pertaining to the area of new green cover or the level of achieved surface reflectivity. A much more limited number of studies has focused on the use of all four strategies – greening, shading, reflecting, and watering – and finds a combined effect of these approaches on maximum daily temperatures to be in excess of 6°F in arid climates, a level of cooling well exceeding the performance of any single strategy and sufficient to mostly or fully offset the urban island effect [65].

In short, an extensive greening of cities combined with managed soil moisture and the use of thermally responsive building materials carries the potential not only to offset continued warming in urban areas brought about through the global greenhouse effect, estimated at present to be about 0.6°F per decade,[4] but to arrest further warming while accommodating additional population growth. No foreseeable greenhouse emissions control program, of any geographic scale – ranging from the individual city to the entirety of global human settlement – can come close to attaining this level of urban cooling in the present century. The body of evidence on urban heat management is scientifically robust, widely validated, and unambiguous on this basic point: Cities can slow and quite feasibly reverse their present rate of warming through built environment strategies implemented at the urban scale and falling fully within the legal authority of most municipal or provincial governments. Urban heat management can be adapted to a wide range of regional climate conditions, requires a budgetary allocation comparable to other types of critical urban infrastructure, and is highly compatible with

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[4] The average decadal rate of change in mean global temperatures since 2000 is estimated from the NASA global mean temperature anomaly dataset as 0.57°F (https://data.giss.nasa.gov/gistemp).

other climate policy goals, such as the reduction of greenhouse gas emissions. Urban heat management can render our cities more resilient and more livable at the same time.

This full-throated endorsement notwithstanding, a radical redesigning of cities to lessen the intensity of heat is not the solution to climate change. Adapting to rising temperatures at the small geographic scale of cities is not the same as changing the underlying global physics driving the global greenhouse effect. The ability to slow the rate of warming in cities is at best a mode of triage to buy much-needed time for global emissions controls to stanch our carbon bleed. And these approaches will not be sufficient to keep cities in the most extreme settings within the bounds of human habitability. The need for sufficient water supplies – fresh or reclaimed – to sustain some level of green cover in urban environments will not be possible in all regions confronting ever-deepening water scarcity.

Radical Adaptation for Heat

It has been my purpose in this chapter to highlight the ways in which extreme heat – a rising threat to human health in cities worldwide – is distinct from other modes of environmental management. Cities cannot be walled off from rising levels of heat in a manner similar to the construction of levees for rising volumes of water, nor can cities be drained of heat from the construction of a series of underground pipes. Heat cannot be trucked away to a landfill or purified at a centralized treatment facility. To manage heat most effectively, cities will need to move beyond traditional management approaches to a set of strategies that are much less centralized and much less engineered. Amplified by the design of the city in all locations and during every hour of the day, heat can only be moderated through a set of approaches that are equally diffuse spatially and temporally. Every building, every roadway, and every open space will need to be assessed for its potential to support a canopy for shading, whether vegetative or structured, for its potential to be rendered more reflective, and for its potential to retain moisture.

In a word, our approaches to managing heat in cities must be much more *dispersive* than conventional modes of environmental management. The first of four principles of radical adaptation to be considered, a dispersive approach to climate adaptation represents a sharp departure from large, centralized public works facilities of the nineteenth and twentieth centuries and recognizes that the physical structure of the city itself must be the focus of our management efforts, as opposed to its byproducts alone. Inherent in this shift from a centralized to a dispersed set of management strategies is a shift, at least in part, from publicly owned facilities to privately owned properties. Through a radical approach to climate adaptation, the city must be redesigned across its entire extent to minimize the hazardous effects of heat. The same is true of water.