Temperature Disparity Comparisons for Campus Heat Vulnerabilities

by

Lauren Futami

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Abstract

For the past several decades, planet Earth has experienced the detrimental effects of climate change like heightened temperatures, extreme weather, and wildlife loss, and to this day, still continues to experience these consequences. Because of this, people at various levels of society – global, country, state, city, community – need to prepare the next steps forward regarding how to live and build in this new and changing environment. In order to prepare, it becomes vital to learn and measure what and how the current ecosystem and landscape are reacting to climate change both for human comfort as well as more efficient energy usage. In this research, climate modules were built and distributed across MIT's campus to measure air temperature, ground temperature, humidity, pressure, and light every three minutes over 24 hours. The campus temperatures were compared with established temperature measurements around the surrounding Cambridge city area as well as Boston Logan airport gathered by Weather Underground. Areas on MIT's campus measured comparable average temperatures throughout the 24 hour measurement intervals with the temperatures measured by Weather Underground, but recorded higher maximum temperatures experienced in the day. Within MIT's campus, the climate modules also recorded varying temperatures, signaling that MIT's campus does not have a holistic temperature, but rather disparate temperature readings depending on the surrounding area and materials. As a result, this research informs MIT's future decisions on possibly energy allocation among existing buildings as well as planning for subsequent construction of new structures.

Thesis Supervisor: David R. Wallace
Title: Professor of Mechanical Engineering

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Chapter 1

Introduction

This research presents the design and implementation of climate modules throughout MIT's campus during the summer of 2022. MIT has been dedicating campus efforts to sustainability, such as its recent climate action plan announcing a declaration for net-zero campus emissions by 2026 and a complete elimination of direct campus emissions by 2050 [12]. Robust research has focused on certain sustainability and resiliency efforts on MIT's campus regarding flood risks and flood modeling. In addition to the campus flood risk projections, MIT's Office of Sustainability is working toward expanding its research into uncovering the possible heat vulnerabilities on campus. Without existing data on the temperatures experienced on MIT's campus, it became increasingly clear that in order to inform campus decisions for the future, MIT needs to have a clear idea on its current state. The following section details the effects of increasing heat on materials, human health, communities, and locally at MIT's campus, which in turn provided insight into the design and implementation decisions of this paper's research methods.

Chapter 2

Background

2.1 Introduction

Since the 1980s, it has been established that the earth has been experiencing climate change on a global scale and will continue to face detrimental effects in the coming years [07][08]. Despite best efforts to counteract this planet-wide malady, the effects of climate change will still need to be faced at varying scales in the present and near future, including but not limited to higher temperatures, more severe storms, rising sea levels, and loss of species [39][41][40][38]. In order to plan on how to withstand these effects, it is vital to understand how climate change will affect the earth at these various scales, especially at a more local level such as state-wide or even county- or city-wide, because it is at these more local levels that effective actions against climate change are made [1][46]. This background section delves into the effects of climate change, specifically in terms of heat, in varying contexts such as toward humans, materials, and locally at MIT's campus. It also reports the current ways that temperature is measured and expounds upon how further research may help to answer the question: at what level do researchers need information on the impact of climate change in order to enact an effective response?

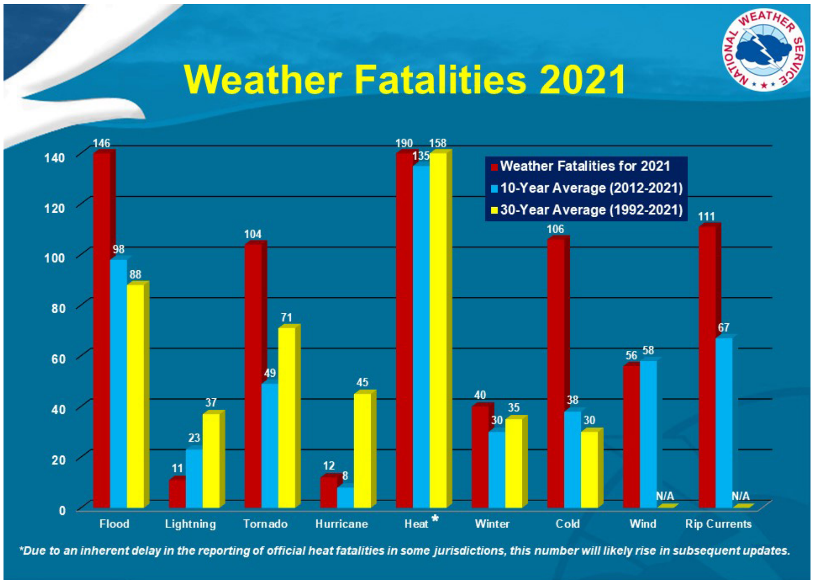

Figure 2-1: Weather fatalities of 2021

2.2 Heat Impact on Humans

Among natural disasters, heat historically claims the most lives each year in the United States (see Figure 2-1) [8]. Furthermore, it has been estimated that climate change is responsible for over a third of the total deaths related to heat across the globe in June 2019 [19].

Although the human body can accommodate exposure to heat, once external temperatures to rise above the natural body temperature of 98.6ºF, the body must begin sweating to cool down [17]. For every 1ºF increase, the body's heat rate increases up to 10 beats per minute, and can begin to experience heat exhaustion such as drowsiness, cramping, and nausea. At 104ºF, the body can transition to heat stroke which can quickly lead to organ shutdown and cardiac arrest. Those especially vulnerable to heat, which include the elderly and the very young, can succumb to these detrimental effects to heat in less extreme weather. Additionally, people can withstand high heat for brief periods of time, but it is when the exposure to increased heat extends to longer durations such as during heat waves, when it becomes much more dangerous for humans [11]. Recent studies have also indicated that humans cannot withstand temperatures and humidity levels as high as once predetermined. Historically, it was believed that humans can withstand a maximum wet-bulb temperature of 35ºC, or 95ºF at 100 percent humidity. However recent research has uncovered that the actual maximum temperature that humans can endure is closer to a wet-bulb temperature of 31ºC, or 87ºF at 100 percent humidity [26]. Furthermore, this new lowered maximum applies to healthy and fit individuals, which indicates that those especially susceptible to heat, such as the elderly or people on medications, will have even lower tolerances to heat. Additionally, this could mean that with the increasing temperatures experienced globally, especially in the urban hubs, humans will be even more susceptible to heat exposure.

This is especially dangerous as current research has shown that currently, about 30 percent of the world's population is already exposed to environmental conditions that can lead to fatal consequences for at least 20 days per year. However, by 2100, even with significant efforts to reduce greenhouse gas emissions, this exposed population will still grow to 48 percent, and in the scenario that greenhouse gas emissions continue to grow, that vulnerable population will grow to around 74 percent [22]. The combination of humans being unable to endure heat as high as once believed as well as the predicted onslaught of higher, more frequent, and extended heat days, means that the human population will face a higher risk of heat related deaths and injuries within the next lifetime.

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This can already be seen locally within the city of Cambridge. Currently, Cambridge experiences around 11 days of temperatures above 90ºF (see Figure 2-2)[7]. While there are around 90 total summer days, the current 11 days of above-90ºF can be reasonably spread out in a way that might mean experiencing a few hot days over the summer, but it would generally be fairly bearable for most of the population. However, as Cambridge teeters toward the 2030 projection of high heat days, the city may begin seeing up to three times as many high heat days, meaning over 30 days of temperatures exceeding 90ºF. This would mean Cambridge will begin experiencing heat over 90ºF for more than a third of the summer months (see Figure 3).

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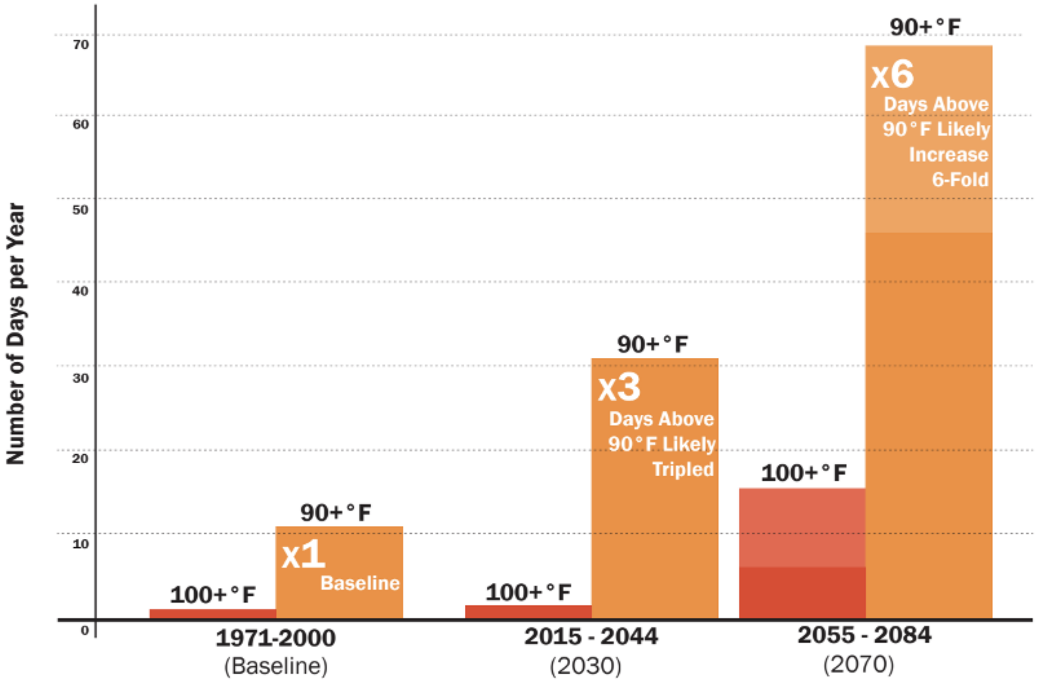


Figure 2-2: Current and future projection of high heat days in Cambridge, Massachusetts

bridge experiences around 11 days of temperatures above 90ºF (see Figure 2-2)[7]. While there are around 90 total summer days, the current 11 days of above-90ºF can be reasonably spread out in a way that might mean experiencing a few hot days over the summer, but it would generally be fairly bearable for most of the population. However, as Cambridge teeters toward the 2030 projection of high heat days, the city may begin seeing up to three times as many high heat days, meaning over 30 days of temperatures exceeding 90ºF. This would mean Cambridge will begin experiencing heat over 90ºF for more than a third of the summer months (see Figure 2-3).

This increase in high heat days would be much more difficult to separate into individual high heat days, and the inflated frequency of consecutive high heat days would expose many to the dangerous effects of heat. Looking at the 2070 high heat day projection, there would only be around 3 weeks of temperatures below 90ºF, which would most definitely endanger Cambridge's population.

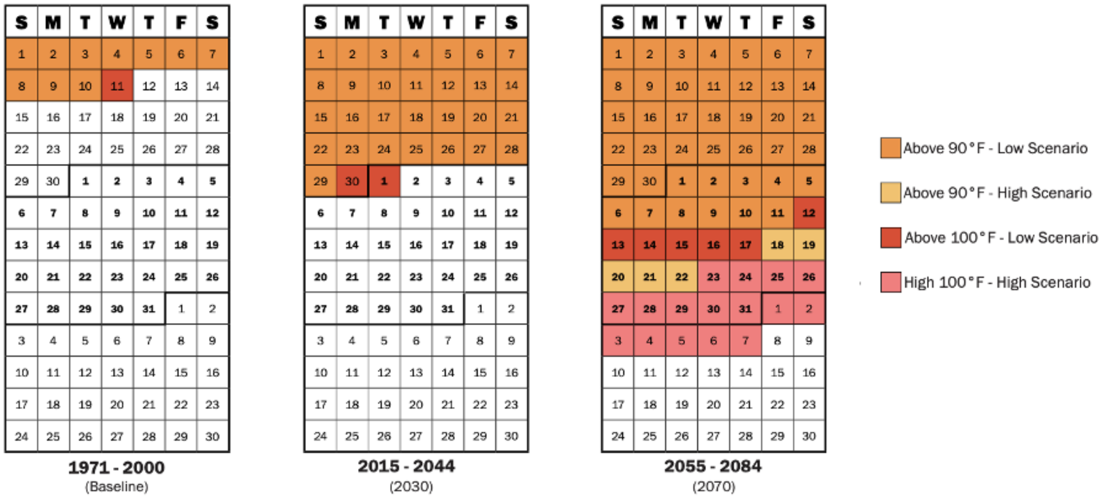


Figure 2-3: Relative increase in possible projected days above 90ºF and 100ºF over a 3-month period

2.2.1 Urban Heat Island Effect

The urban heat island effect is the increase in temperature felt within urban city environments compared to the surrounding rural areas because of the prevalent use of man-made materials like concrete and asphalt [35]. These materials frequently used in buildings and roads absorb solar radiation in the form of heat and not only raise daytime temperatures, but keep nighttime temperatures high as well [2]. Other causes that contribute to urban heat islands are the lack of trees and greenery in highly urbanized areas which leads to a decreased amount of shade as well as a decrease in the cooling effect from evapotranspiration. Heat as a byproduct of energy usage from technology like air conditioning and vehicles also contributes to the urban heat island effect [4].

The particular danger of the urban heat island effect is the lack of heat dispersal at night, which means that those who live in urban areas do not experience a relief from heat they normally would feel during the nighttime [18]. Without relief from heat for an extended period of time, humans can begin experiencing the ill effects of heat. The urban heat island effect can also raise what would normally be an 88ºF summer day to a temperature of 90ºF or over, which means Cambridge could possibly be seeing even more than the 30 days of projected high heat days (see in Figure 2-2).

The effect may also raise urban temperatures to a degree that the power grid cannot handle, and if rolling blackouts begin occurring in the summer, this would expose all of the Cambridge population to heat as well.

The urban heat island effect contributes to the greatest difference in temperature at night. This is because of the natural cooling effect felt at night. However, in dense urban areas, the common use of asphalt and concrete absorb solar radiation during the day and slowly disperse it throughout the night, keeping temperatures in cities high. This eliminates the relief that people living in cities would normally feel at night in surrounding rural areas. It is also important to note that the urban heat island effect also contributes to large temperature differences during the winter time. This means that cities will generally feel warmer during the winter, and there may even be less energy spent in heating buildings as well [33]. However, the convenience of warmer winters does not necessarily offset the dangers of high heat in the summer, (see Figure 2-1), as deaths attributed to heat are on average four times higher than those attributed to cold.

2.3 Heat Impact on Materials

Albedo is the measure of solar radiation reflected off of a material, which is measured on a scale of 0 to 1. A value of 0 would correlate to a completely black surface that absorbs all solar radiation, and a value of 1 would mean the material reflects all incident radiation [45]. Various natural and artificial materials found in urban landscape and architecture have differing albedo (See Figure **??**).

Although both man-made and natural materials show similar albedo measurements, vegetation such as trees and grass participate in evapotranspiration, the release of water into the air that subsequently dissipates the surrounding heat [31]. Evapotranspiration does not occur nearly as readily with impervious surfaces such as concrete or asphalt because water quickly runs off before evaporating. Tree cover also reduces the amount of solar radiation exposure to artificial surfaces that easily absorb solar radiation during the day and consequently release the energy as heat

Surface	**Albedo**
Soil - dark and wet	0.05
Soil - light and dry	0.40
Sand	0.15-0.40
Grass - long	0.16
Grass - short	0.26
Crops	0.18 - 0.25
Tundra	0.18 - 0.25
Forests - deciduous	0.15 - 0.20
Forests - coniferous	0.05 - 0.15
Water - small zenith angle	0.03-0.10
Water - large zenith angle	0.10-1.0
Snow	0.40
Ice - sea	0.30-0.45
Ice - glacier	0.20-0.40
Clouds - thick	0.60-0.90
Clouds - thin	0.30-0.50
Corrugated roof	0.10-0.15
Colored paint	0.15-0.35
Trees	0.15-0.18
Asphalt	0.05-0.20
Concrete	0.25-0.70
Grass	0.25-0.30

Table 2.1: Albedo measurements of natural and artificial surfaces

during the night [6].

The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) publishes standards to inform the heating, ventilating and air conditioning (HVAC) industry guidelines [16]. Currently, ASHRAE publishes data from 12 sites, usually at local airports, for the entire state of Massachusetts. Currently, the greater Boston area relies on the information gathered by ASHRAE at the Boston Logan International Airport location, due to its proximity. Boston Logan Airport, however, is comprised of wildly differing architecture and landscape than that of MIT's campus. The Charles River, which acts as a large body of water, also surrounds Boston Logan Airport on nearly every side, which can greatly reduce the temperatures experienced at the airport location [28].

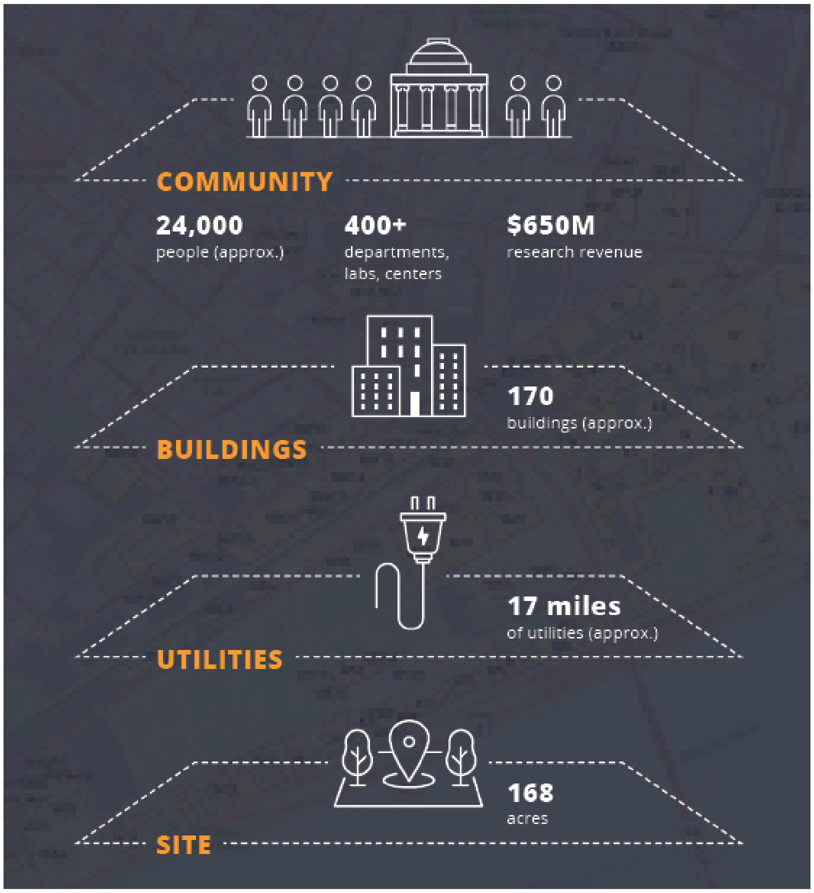


Figure 2-4: MIT Office of Sustainability Layers of Resiliency

2.4 Heat Impact at MIT

MIT currently has its own Office of Sustainability which heads efforts like the Climate Resiliency Committee whose aim is to create and foster climate resiliency at all levels at MIT, majorly focusing on flood risks and minorly on heat. These levels have been identified as the layers of resiliency on campus which includes site, utilities, buildings, and community [3]. The site layer includes MIT's general campus acreage which sees 168 acres of natural and built landscape. The utilities layer focuses on the electrical, gas, water, and sewage aspect of the campus while the buildings layer aptly concentrates on the various living, research, and education structures on campus. Lastly, the community level addresses the people on campus, including but not limited to the students, staff, and faculty who occupy many teaching, researching, and living roles at MIT. See Figure 2-4 for MIT's layers of resiliency.

Assessing the heat risk at MIT on the site layer includes evaluating what may fail as temperatures rise on campus. Current risks include asphalt in use on campus today faltering under summer daily maximum temperatures which can cause the binder in asphalt to break down, thus compromising its structural integrity. This would mean that asphalt installed only a few years ago with an estimated lifetime of 50 years would be unable to live up to that approximation due to climate change [47]. This adds unnecessary costs due to inevitable replacement and additionally wastes asphalt material which results in greater campus carbon emissions [48]. As the asphalt binder breaks down, it also contaminates all objects that contact it, which could create damage to vehicles, campus landscape, and even pedestrian footwear. Potholes may also become a larger repair issue and create hazardous conditions for the community should the surrounding asphalt continue to break down.

On the utility level, the Climate Resiliency Committee is assessing what the peak demand may be with rising ambient heat levels in the city, especially when it is magnified by the urban heat island effect. There may not be enough electrical generation if the demand for electricity, especially in the form of air conditioning, begins increasing and is sustained for longer periods of time [20][25]. Transformers used in the electrical grid on campus also face the risk of a lower life cycle in high heat, as well as explosive failures [27]. The IT department also relies on physical switches that are vulnerable to failure if faced with high heat environments.

At the building level, it is important to note that not all MIT buildings are air conditioned in the summer. However, as temperatures increase, there is a real concern that MIT will need to begin installing new air conditioning infrastructure into buildings that are normally left uncooled. With increasing temperatures, lab spaces on campus that need to rely on constant temperature environments for lab equipment and research experiments are put at risk if the demand for air conditioning exceeds the amount that MIT can reliably handle. Due to heat physically rising throughout the day, lab spaces on higher stories are more vulnerable to increased heat. Electrical equipment that occupies building roofs are also especially prone to this type of heat phenomenon.

The lack of air conditioning in buildings across campus also affects the MIT campus at the community level since there are also several dorms on campus that do not provide air conditioning to students. If temperatures in May begin feeling like summertime temperatures, students will not have areas with suitable environments in which to study and conduct research. Sleep schedules at night can also be deeply interrupted [44], and the resulting exhaustion would be detrimental to the community if students cannot undertake their regular social and scholarly activities. The threat of increasing temperatures rendering current pedestrian pathways unusable also affects the campus at the community level [36][29]. Based on the current materials used as well as the existing landscape and architecture, certain pedestrian pathways on campus with high foot traffic could be impractical in summertime temperatures.

According to the US Department of Energy, the building sector is responsible for about 41 percent of total energy use, making it the largest energy consumer in the country [43]. As such, MIT is looking for effective ways to reduce energy consumption in its own buildings in an effort to reduce at least 32 percent of emissions by 2030 [23]. This would include evaluating the lifecycle analysis of current and future buildings and improving upon these strategies during the entire lifetime, in order to minimize emissions where possible [10].

For this reason, it is important to note that on MIT's campus in the summer, external air is pumped through vents into campus buildings and immediately cooled before being dispersed through the surrounding structures to cool those respective buildings. On particularly sweltering days, MIT will spend more energy resources cooling the hotter air collected from the outdoors from these vents. If these areas where the vents are collecting the external air from can be made cooler, MIT will not have to expend unnecessary energy to cool this air. Practices like exchanging impervious surfaces to vegetation, allowing for more wind activity to alleviate stagnant heat buildup, or installing natural or manmade structures to provide shade are among various methods needed to encourage a lower air temperature at these vents, which is an immediate and relatively low-cost way to reduce the energy spent cooling the air for building use. Thus, measuring various areas around MIT's campus will help to inform the decision-making behind this activity, such as whether or not it is even worth attempting to measure the temperature disparities at these vents if the differences are negligible.

2.5 Current Methods of Measuring Temperature

2.5.1 Satellites

One current method to measure surface temperatures to monitor climate change utilizes climate satellites that capture temperature images of the Earth as they orbit the planet. These images are then stitched together to form a heat map of large surface areas. This method is advantageous for observing aggregate temperatures on a larger scale (city-, state-, planet-wide) but become more difficult to observe temperatures on a smaller, more local scale. The resolution of these satellites are accurate to about 500 to 600 square meters, meaning temperature details can be muddied when attempting to see heat maps on a smaller scale, say within a city or local community [42]. Using these climate satellites is useful for planet-wide comparisons in temperature data, such as looking at the differences between countries or states.

Despite heat being a relatively recent and emerging topic of research at MIT, there have already been several heat models created in Cambridge and Boston to help evaluate the risks of heat on a city level [15]. See Figure 2-5 for the heat map created by the city of Cambridge using weather satellites.

Using the satellite data, the resulting heat map shows a general temperature range of 80ºF-90ºF throughout the city of Cambridge. There are hotter pockets shown in orange, meaning that those areas will feel a temperature range between 90ºF-103ºF, but the most prevalent temperature range lies in the yellow 80ºF-90ºF range. Although there are slight deviations in the overall map, the visual conveys that if there are temperature disparities within the 500 to 600 square meter resolution of the climate satellites, it is not captured within the data collected.

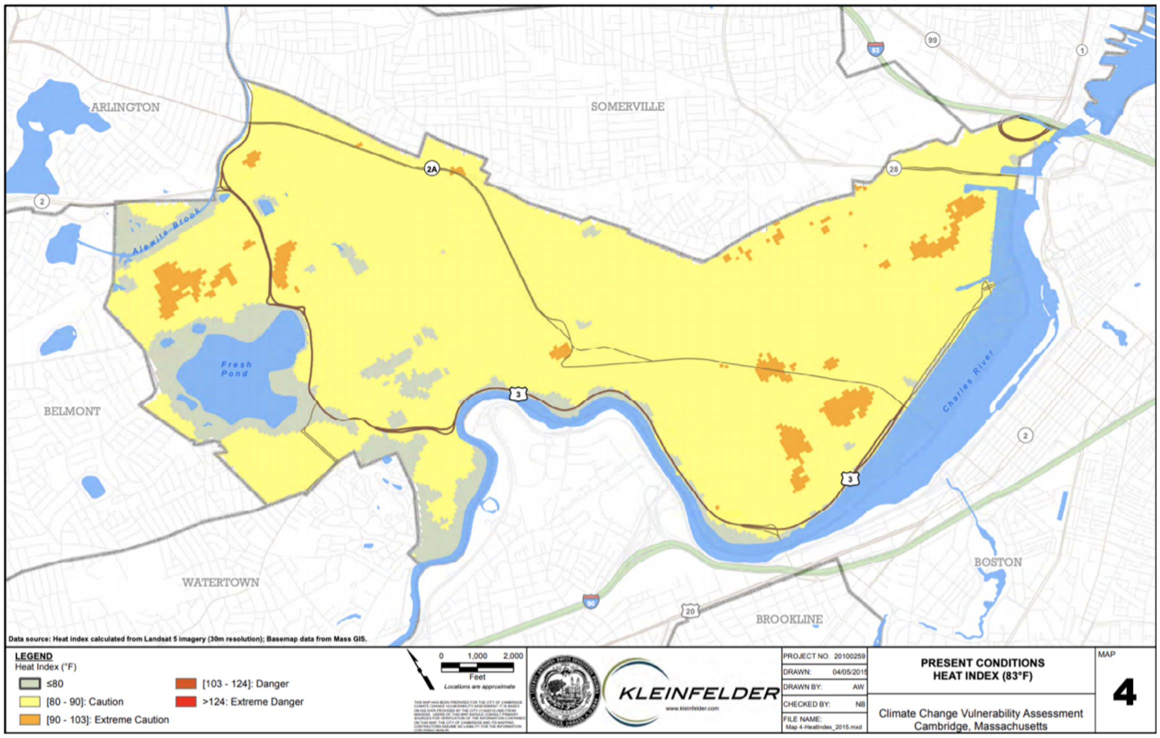


Figure 2-5: Heat island map of Cambridge under current baseline conditions

2.5.2 Automobiles

Another method of creating heat maps was implemented in a collaboration between the Museum of Science and Northeastern University. The data was collected by mounting sensors onto cars and having volunteers drive those cars around Boston in predestined routes at 6am, 3pm, and 7pm for several days throughout the summer of 2019. The sensors logged temperature and humidity data every second for each of these drives. Compiling the data from these sensors created a hyperlocal heat map of Boston that shows a wider range of temperatures throughout Boston versus the heat map created by the city of Cambridge [9]. See Figure 2-6 for the hyperlocal heat map of Boston created by the Wicket Hot Boston project.

This is not to say that one heat map is a better map than the other, it is just to show how various ways to collect data can create different visualizations of heat maps. This also helps start the conversation of which heat map would be more useful for MIT to use on a campus level. For instance, the data collected to create the city of Cambridge's heat map shown in Figure 2-5 was also used to show projections of

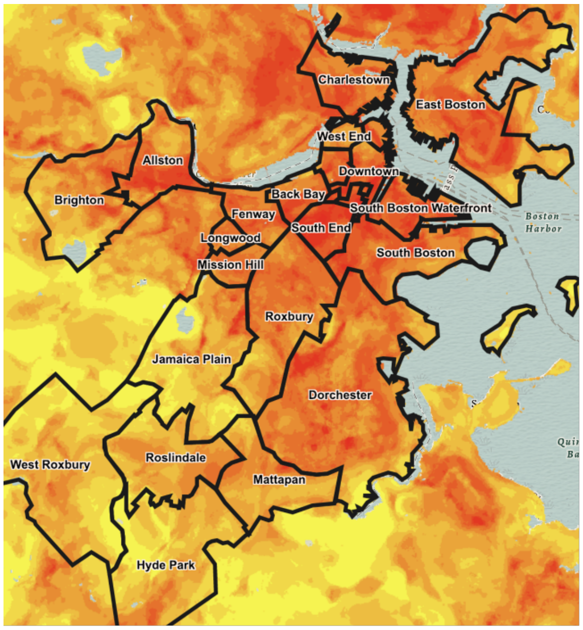


Figure 2-6: Hyperlocal heat map of Boston under current conditions

the heat map in Cambridge in 2030 and 2070, both shown in Figures 2-7 and 2-8. In this way, Cambridge can see how the general temperature ranges may change in the coming decades in relative areas across the city, which could not necessarily have been done with the data collected for the Museum of Science and Northeastern University's hyperlocal heat map.

In the same vein, the hyperlocal heat map can be used to identify current detailed areas of Boston that may be susceptible to heat and the urban heat island effect. For example, the urban tree canopy was also mapped for the city of Boston using satellite imaging in 2016, shown in Figure 2-9. By superimposing the Boston heat map with the urban tree canopy, as shown in Figure 2-10, it becomes clearer to see how the areas of Boston experiencing higher temperatures align with the areas that do not have much tree cover, whereas the rural areas with higher tree canopy experiences lower temperatures. This correlation might not have been possible using the more general heat map of Cambridge due to the lack of heat details.

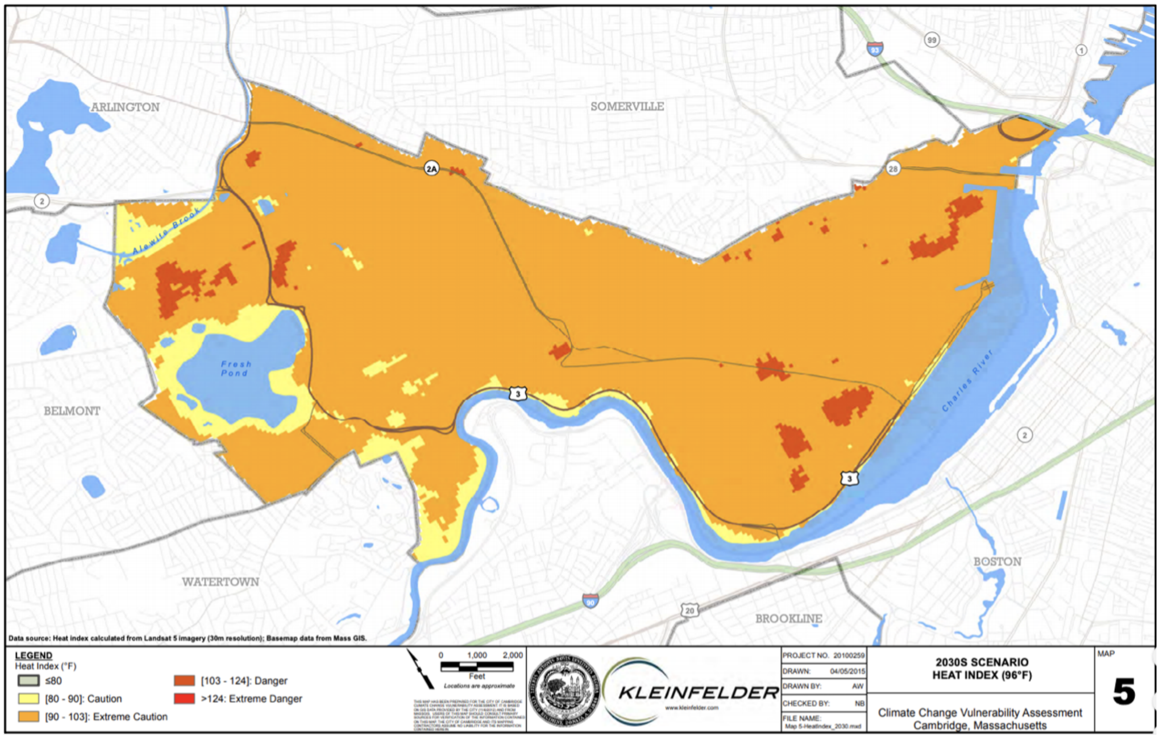


Figure 2-7: Heat island map of Cambridge under 2030 conditions

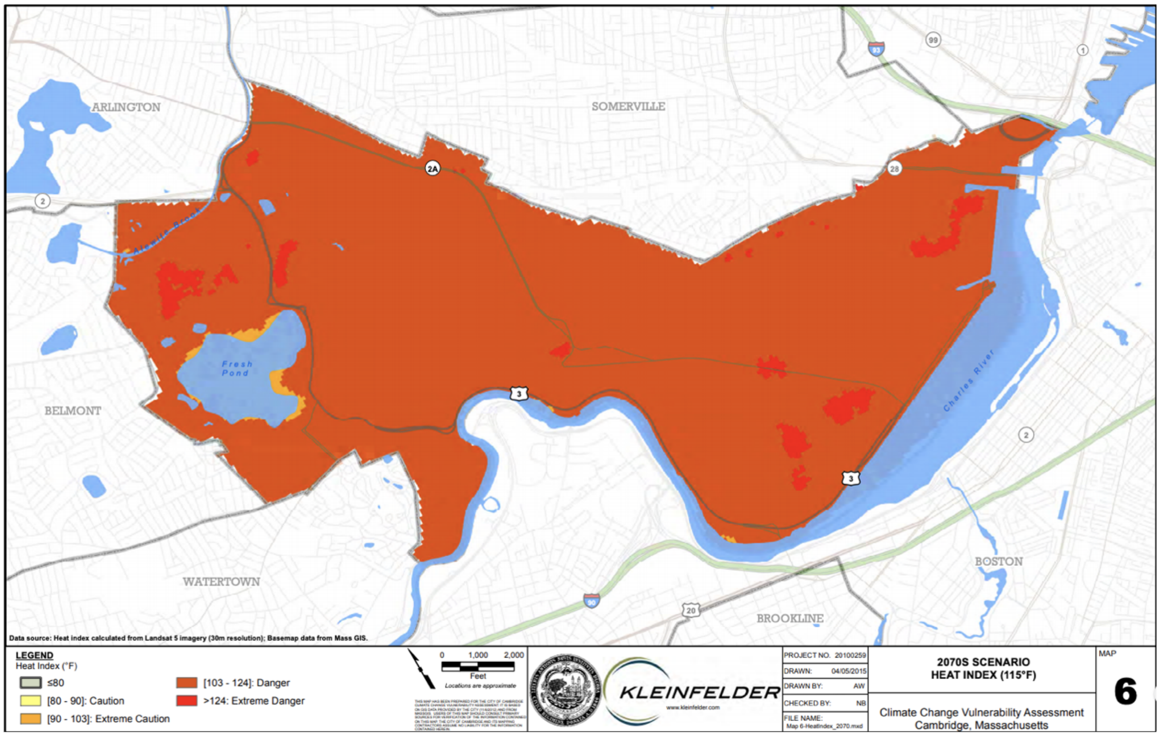


Figure 2-8: Heat island map of Cambridge under 2070 conditions

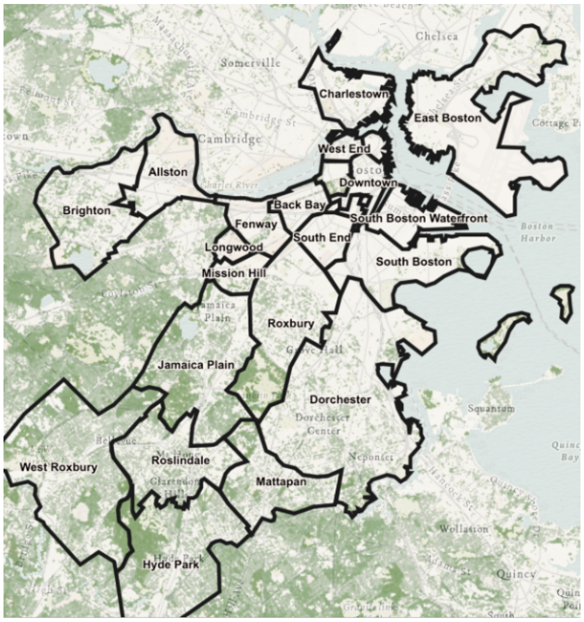


Figure 2-9: Tree canopy coverage in Boston Metropolitan Area

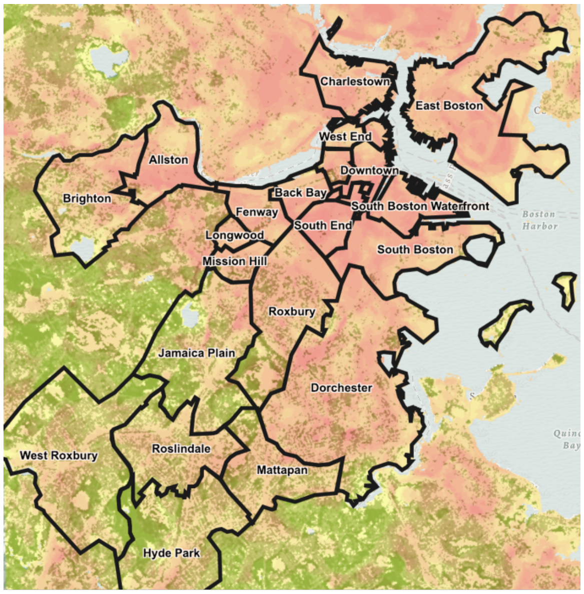


Figure 2-10: Superimposition of Boston urban heat island map and tree canopy coverage

2.6 Study Motivation

MIT's renewed commitment to energy sustainability, the gap in knowledge of current campus conditions, the current methods of studying temperature, and even anecdotal evidence created interest in studying the ongoing temperature environment at a more local level. MIT's Office of Sustainability's recent robust research into the effects of various flood potentials on campus has exposed the risks to campus that MIT is currently unprepared for. This research revelation has also spurred concerns about how increasing and extended high temperatures may also display campus heat vulnerabilities. Additionally, the initial review of how temperature can be studied on a global and somewhat more local city level uncovered the questions of how temperature might be studied on a campus scale and what it could reveal about the campus itself. Not only has temperature not been rigorously studied specifically at the campus level at MIT, no formal technique or process currently exists for measuring temperature at a campus scale. Though incidental, anecdotal evidence about heat effects on campus have also led to expanded interest in studying the phenomenon. Classrooms adjacent to enclosed parking lots have felt hotter and stuffier than non-adjacent classrooms, even into the evening and night. The inability to control the temperature in these classrooms resulted in opening windows, that also open into the parking lot, which allegedly did not relieve the classroom heat. Students living in MIT dorms over the summer often take shelter on campus labs to escape the enveloping heat in their living areas. Students taking pedestrian pathways on campus tend to prefer traversing one side simply because the other accumulates too much heat. Therefore, due to all of these occurrences, planning and conducting research that may pave the way for continued temperature investigation on the campus scale will benefit MIT in illuminating possible concerns about heat vulnerabilities on campus.

Chapter 3

Methods

Climate modules were designed and built in order to measure and compare the temperature at difference campus environments as well as the temperatures measured by external sources.

Each climate module measures ground temperature, air temperature, humidity, light, and pressure. These measurements are taken at 3 minute increments for at least 24 hours at a time. The climate devices are self-contained and free-standing. 20 identical devices were constructed for deployment to measure varying campus environments over the same time period.

The climate modules were created in order to optimize cost, form, and function. Because this research relied on 20 modules being designed and constructed, it was important to keep the individual cost of each module as low as possible without compromising the integrity of the data being collected. After an initial survey of the campus grounds, it became well aware that the climate modules would be interacting with a wide variety of environments and variables. Being unsupervised outdoors meant subjecting the module to all types of weather, wind activity, unpredictable terrain, and possible human interference, all of which the climate module would have to withstand.

3.1 Climate Module Design and Build

The first climate module iteration was composed of foamcore board cut into pieces to create a 20”x20”x20” box as the main housing for the sensor components. A 48” long PVC tube sat vertically in this foamcore board housing. The main part of the housing protected an MLX90614 infrared (IR) temperature sensor that measured the ground temperature, and an AHT20 ambient temperature sensor that measured the air temperature and surrounding humidity. The MLX90614 sensor stuck out from close to the bottom of the housing and measured an inch above the surface being measured, while the AHT20 temperature sensor snaked upward through the PVC tube to be able to measure the air temperature and humidity at 48 inches above the surface being measured, per the guidelines for measuring air temperature [24]. A rechargeable, portable power supply powered the two sensors, all wired onto a breadboard, to ensure lasting power and testing in outdoor conditions. Outdoor testing with the first iteration involved placing the foamcore housing onto level pavement in the parking lot between Building 3 and Building 5 of MIT’s campus.

The housing proved to be robust in an outdoor environment, maintaining its position for 24 hours, and with the electronics clocking the temperature and humidity data every minute. Despite the ability to withstand the elements for 24 hours, the foamcore housing would not hold up to weather like rain or snow, as the external fibers would deteriorate when exposed to water. The general size of the housing would also need to be reduced in order to optimize how many modules would be able to be handled and transported. Even with a rolling cart, a maximum of six modules of this size would be able to be comfortably transported by an individual. In order to optimize this number, the profile would need to be reduced.

The second climate module iteration replaced the foamcore housing with a 8.6"×6.7"×4.3" junction box with a transparent lid. This iteration instead had a 48” long acrylic tube that also stood vertically, the bottom of which protruded from the junction box, and the top of which had a sensor weather shield attached in order to protect the tube from taking in water in the case of rain. This second iteration also included the

MLX90614 and AHT20 sensors, but also included a VEML7700 lux sensor to measure the amount of light hitting the top of the module, as well as a BMP280 sensor which measured the surrounding pressure. The MLX90614 sensor similarly protruded from near the bottom of the junction box, protected by a 3D printed arm from water damage while measuring the ground temperature. The AHT20 sensor also similarly wound through the acrylic pipe and sat 48 inches above the ground, measuring the ambient air temperature and humidity. The VEML7700 lux sensor was attached to the transparent lid of the junction box and measured the light that hit the lid, which would help determine whether or not the amount of light hitting the module correlated with the temperatures measured. The BMP280 sensor sat within the junction box measuring the surrounding pressure to also help illuminate if the pressure measured had an effect on the temperature measured. The four sensors were connected to a breadboard and powered with four AA batteries in order to minimize the physical profile of the power supply used in the first iteration.

During testing for the second climate module, the electronics within the second climate module worked as expected, which wrote the temperature, humidity, light, and pressure measurements onto a microSD card every three minutes. Writing the data changed from every minute in the first iteration to every three minutes in the second iteration because the data being measured every minute proved to be extraneous. External temperature sources logged their temperature data on the order of five minutes to sixty minutes [14][13], which also helped inform the second iteration to minimize the extraneous data while optimizing the frequency of data collected.

The third and last climate module iteration demonstrated a design shift after outdoor testing with the second iteration. After testing with data records writing every one minute, the third climate module iteration changed to recording data every three minutes to reduce needless information collected as well as preserving the module's battery life. The second climate module iteration performed poorly with varying terrain. Due to the top-heavy nature of the second iteration having a small area to support the 48 inch long pipe, it tended to fall over on landscape with even a very minor grade. On landscape with no grade even proved difficult if wind was present,

Figure 3-1: Climate module iterations. From left to right: foamcore iteration, acrylic tube iteration, tripod iteration

as it would knock the climate module over as well. As such, the third climate module iteration pivoted form factors and maintained the box housing for the electronics and replaced the 48 inch pipe with a tripod mounted below the electronic box housing that could extend to 48 inches. The tripod base allowed for three points of contact with the ground being measured, which provided a more stable structure for surfaces with any grade as well as resistance to wind interference. A 10 inch pipe was also installed on the bottom face of the electronic box housing to provide a rigid structure to lead the MLX90614 infrared red sensor closer to the ground being measured so that its measuring circumference was focused closer to the ground surface. The electronic box housing also became entirely opaque to draw less curiosity to the internal wiring in order to deter possible human interference in public areas. Instead, a two inch diameter hole was drilled into the top face of the box with a two and half inch transparent, acrylic circle attached over the hole with epoxy to provide a window for the VEML7700 lux sensor. A PVC elbow attachment was also epoxied to the side face of the electronic box housing in order to provide adequate environmental exposure for the AHT20 temperature and humidity sensor and the BMP280 pressure sensor while also keeping the housing waterproof from rainfall. Lastly, a hole was drilled into the bottom face of the electronic box housing to provide an anchor point for the tripod. See Figure **??** for the climate model iterations.

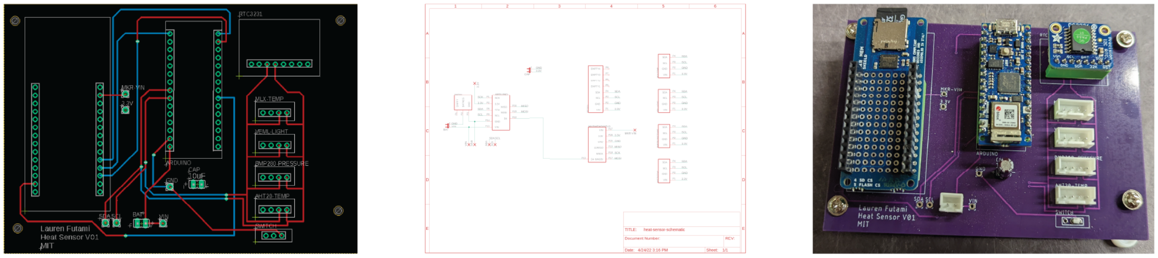


Figure 3-2: Evolution of the climate module circuit design. From left to right: circuit design, circuit schematic, final PCB

3.2 Hardware

Due to the research goal of creating 20 climate modules, the key component became designing and producing a printed circuit board (PCB). PCBs allow for the generation of a large number of identical circuit boards, which is useful to preserve time spent on any individual climate module. Creating the PCB began from prototyping the climate module circuit on a breadboard, then moving to a more permanent protoboard, then finally into the design stages of the PCB in Autodesk's Eagle software. See Figure 3-2 for the evolution of the circuit design.

The general workings of the climate module circuit revolved around the Arduino Nano 33 IoT. Initial designs for the climate module electronics included wirelessly sending the sensor data from the climate module to a remote server that would automatically populate a live data sheet that would graph the incoming climate data. The Arduino Nano 33 IoT microcontroller is capable of wirelessly sending this information that other microcontrollers are not; however, outdoor areas on MIT's campus had unreliable network connectivity that rendered this design impractical. Nevertheless, because the current climate modules are still comprised of this Arduino Nano 33 IoT, they are theoretically able to wirelessly send data given the proper circumstances and coding.

The two non-sensor components connected to the Arduino Nano 33 IoT microcontroller includes the Arduino MKR MEM shield and the Adafruit DS3231 Precision Real Time Clock breakout board. The Arduino shield acts as a microSD card reader and writer that enables the Arduino Nano 33 IoT microcontroller to write climate data onto the microSD card. In this way, the climate module is writing data locally within itself and requires periodic collection. The Adafruit DS3231 Precision Real Time Clock breakout board is initialized separately from the climate module, which allows it to set its internal clock. Once a separate CR1220 battery is placed into the real time clock, it will independently keep global time, even if the rest of the circuit it is connected to loses power. In this way, the Arduino microcontroller is able to add time stamps to all environmental data it collects, which includes the day, month, year, hour, minute, and second. This real time clock's accuracy is guaranteed by the integration of the timing crystal within the chip which is monitored by a separate temperature sensor, correcting any timing changes caused by heat. This is crucial due to the climate module's exposure to heat during regular use.

The climate module is powered by eight AA batteries providing at most 12 volts of power to the circuit. This lasts the climate module about three weeks of use under mild outdoor temperature conditions, while writing the data once every three minutes. Under warmer environmental conditions, the climate module battery power will diminish and battery life may last closer to one week.

The four sensors connected to the climate module include an MLX90614 infrared temperature sensor, an AHT20 temperature and humidity sensor, an Adafruit VEML7700 lux sensor, and an Adafruit BMP280 barometric pressure and altitude sensor. The MLX90614 infrared temperature sensor's aim is to measure the ground temperature of the material below the climate module. The AHT20 temperature and humidity sensor measures the ambient air temperature and relative humidity 48 inches above the ground surface. The Adafruit VEML7700 lux sensor measures the amount of light exposed to the climate module, and the Adafruit BMP280 pressure sensor likewise measures the surround pressure. These sensors are all connected to the Arduino microcontroller by way of I2C communication, which allows for simplification within the circuit design. Each sensor is connected to the board with a 12 inch wire lead which allows each sensor to be placed around the climate module interior for its specific measurement it is collecting.

The climate module electronic housing was created by altering a third party junction box. Naturally waterproof, it also accommodates electronics with its mounting plate on its bottom surface. This allowed for the PCB to be mounted into the electronic housing with standoffs in order to ensure physical separation from water in the unlikely event that water penetrates the housing. Four holes were drilled into the box. One two inch hole was drilled into the top surface and sealed with a clear, acrylic circle to allow for a viewing port for the Adafruit VEML7700 lux sensor. A 1.5 inch hole was drilled into the underside of the electronic housing and fitted with a 1.5 inch diameter acrylic tubing measuring to 10 inches long in order to provide a conduit for the MLX90614 infrared temperature sensor to gain closer proximity to the ground surface it measures. A 2.5 inch hole was drilled into the side of the electronic housing and also fitted with a 2.5 inch diameter PVC elbow that provided the interface for the AHT20 temperature and humidity sensor as well as the Adafruit BMP280 pressure sensor. This PVC elbow interface allowed the sensors adequate exposure to the surrounding environment for measuring while also shielding them from any weather above. Lastly, a 0.25 inch hole was drilled into the center of the underside of the electronic housing to accommodate a mounting point for the tripod. See Appendix A for the complete bill of materials.

3.3 Software

The software running the code to collect the climate module data was created primarily in C++ within Arduino IDE. The code ran on the Arduino Nano 33 IoT microcontroller and began by initializing the microSD card breakout board, then the MLX90614 infrared temperature sensor, then the AHT20 temperature and humidity sensor, then the VEML7700 lux sensor, then lastly the BMP280 pressure sensor. It created a data string that included sensor data such as air temperature, ground temperature, relative humidity, light, pressure, and the current time. The Arduino then wrote this data string onto the microSD card and looped the data collection every three minutes. See Appendix B for the full code breakdown.

3.4 Placement

3.4.1 Weather Underground Stations

Climate data for four non-MIT campus areas were collected using Weather Underground stations in Cambridge and Boston. These stations are used to collect weather data for accurate aggregate forecasting for cities across the United States [30]. Because these stations are used to predict weather and heat patterns, the Weather Underground data is collected in this research to compare to the climate module data being collected directly on MIT's campus. Although MIT is situated within Cambridge, there are currently no working Weather Underground stations on the campus to represent it in the aggregate city forecast. Comparing the data from the Weather Underground stations with the campus climate modules will help to determine whether granularity is needed for more accurate weather and heat reporting.

The Weather Underground station data being collected are from Central Square, East Cambridge, the Port, and Boston Logan Airport. The Central Square, East Cambridge, and the Port stations are being selected for data collection due to their proximity with MIT's campus, and the Boston Logan Airport station is being selected due to its importance in ASHRAE reporting. The Weather Underground stations record time, air temperature, dew point, humidity, wind direction, wind speed, wind gust, pressure, precipitation rate, precipitation accumulation, UV, and solar exposure, though this research focused on the time, air temperature, and humidity data. See Figure 3-3 for all Weather Underground station positions in relation to MIT's campus.

3.4.2 MIT's Campus

To measure MIT's campus, three climate devices were placed in up to six distinct areas on campus, which allowed for at most 18 climate devices to be deployed at any given time, while having 2 spare climate devices in reserve. It was important for this research to measure a variety of surfaces within a variety of areas across MIT's campus.

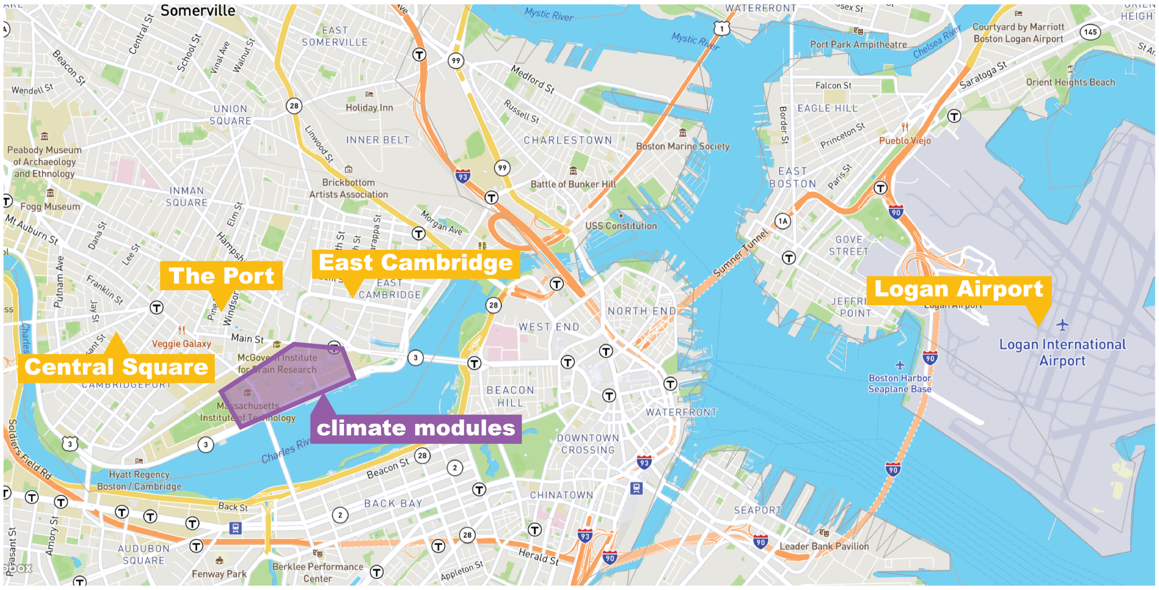


Figure 3-3: Mapping of Weather Underground stations in relation to the campus climate modules

The areas measured include: the courtyard behind Fariborz Maseeh Hall, the parking lot between Building 5 and Building 3, the exterior walkway between Building 31 and Building 13, a recently established green space called The Hive, the courtyard between MIT Medical and the List Visual Arts Center, and the also recently finished outdoor courtyard next to the MIT Welcome Center. These areas were all chosen for measurement because together, they represent the large variety of environments found in MIT's sprawling urban campus. See Figure 3-4 for all MIT climate module positions.

3.4.3 Maseeh Courtyard

The courtyard behind Fariborz Maseeh Hall was important to measure because it is an area that could affect the surrounding building depending on the amount of heat that can accumulate within the courtyard. The surrounding building is an undergraduate dormitory that houses almost 500 students [32]. Maseeh Hall also contains a dining hall that increases the traffic in and out of the building. As such, this outdoor courtyard was of interest to measure since it can represent the living, studying, and eating conditions that students face at MIT. Maseeh Hall has air conditioning in the

Figure 3-4: Mapping of climate modules on MIT's campus

(a) Climate modules denoted by M1, M2, and M3

(b) Contextual surroundings for M1

(c) M1 measuring grass surface material

(d) Contextual surroundings for M2

(e) M2 measuring concrete surface material

(f) Contextual surroundings for M3

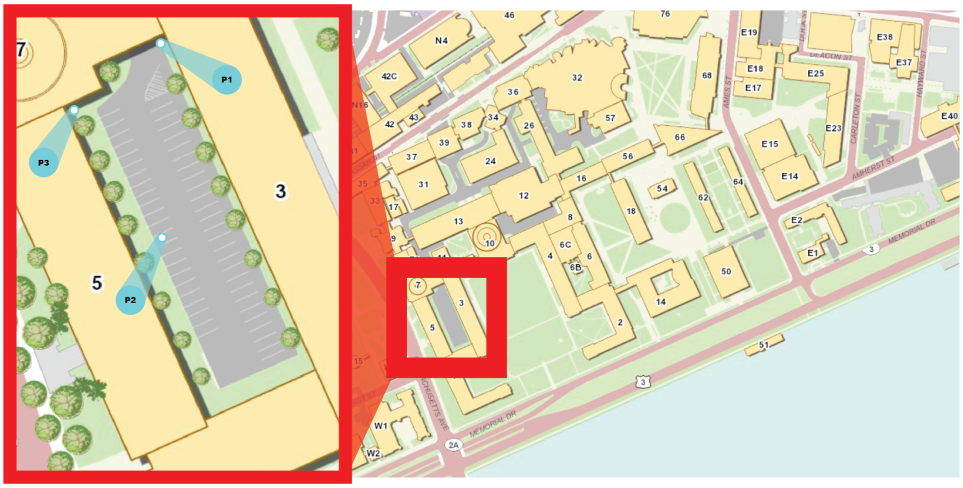
(g) M3 measuring vegetation surface material

Figure 3-5: (a) Placement of three (3) climate modules at the courtyard in Maseeh Hall hallways but not in individual rooms [34], which means that if student rooms facing the courtyard are attempting to cool down, it may not be possible for students to open windows for relief if the courtyard itself contains high heat. In the worst case scenario, this poses a risk to student wellbeing.

Three climate modules were placed across the Maseeh courtyard to record environmental data. The first climate module in this area, denoted by "M1," was placed on the western side of the courtyard in a planter adjacent to the western wing of the Maseeh dorm. It is measuring the soil and small shrub material beneath, and it is surrounded by larger bushes and various plant life. It also sits near an entrance to the western wing of Maseeh which indicates pedestrian traffic near where the climate module is measuring. The second climate module, denoted by "M2," was placed in the center of the courtyard on top of paver material. It is surrounded by benches and sits near the central entrance into the courtyard from the main Maseeh building. Due to its proximity to the benches, it measures the temperatures experienced by students that would be sitting in the area. Because it is also near the glass outlook from Maseeh, it is also measuring an area that would influence the temperatures in the central Maseeh building. Lastly, the third climate module, denoted by "M3," sits on the opposite but symmetric end of the Maseeh courtyard from the M1 climate module. Likewise, it is measuring soil and shrub material while sitting adjacently to the eastern wing of the Maseeh dorm and also near the eastern wing entrance. This measures different environmental data from the M1 climate module, however, due to the varying sunlight each sensor is exposed to throughout the day as the sun passes from east to west. See Figure 3-5 for Maseeh climate module positioning details.

3.4.4 Parking Lot Outside Building 3

The parking lot situated between Building 3 and Building 5 was of interest to measure because it is a somewhat unusual layout, being flanked on all sides by buildings at least four stories tall and the surface being majorly made up of asphalt for parking, while it is also bordered by planters on most sides. The surrounding buildings reduce the amount of wind that can sweep through the area and help dispose of the stagnant



(a) Climate modules denoted by P1, P2, and P3

(b) Contextual surroundings for H1

(c) H1 measuring concrete surface material

(d) Contextual surroundings for H2

(e) H2 measuring asphalt surface material

(f) Contextual surroundings for H3

(g) H3 measuring vegetation surface material

Figure 3-6: Placement of three (3) climate modules at the parking lot between Building 3 and Building 5 heat, especially that which is absorbed and released by the asphalt, but the presence of planters and vegetation that encircle the area would contribute to mitigating the heat initially absorbed. This combination of differing ground components in addition to the abutting buildings being composed of labs and classrooms that could be negatively affected by possible heat accumulation in the area contributed to the need to measure this parking lot.

The first climate module in this area, denoted by “P1,” was placed in the northeastern corner of the parking lot. It sits atop concrete material and is surrounded on two sides by Building 7 and Building 3. Because it is in the corner, it also experiences very little wind activity, which means heat dispersal would also be decreased. The P1 climate module also sits next to a loading dock used to load and unload various equipment to labs and administration, as well as a space occasionally used for student projects. Due to its proximity to the loading dock, the P1 climate module measured temperatures experienced by those likely to be undergoing physical work throughout the day in this area. The second climate module, denoted by “P2,” was placed in the center of the parking lot on the western side in an area between two parking spaces. Although measuring the asphalt, it is still directly adjacent to soil and vegetation material that runs along the length of the parking lot. By recording asphalt temperature, the P2 climate module is likely measuring the temperature experienced by those who pass through the parking lot to use their cars, as well as the temperature that those cars are idly sitting in during the day. Lastly, the third climate module, denoted by “P3,” sits in the northwestern corner of the parking lot atop soil material, unlike the P1 climate. However, like the P1 climate module, the P3 climate module is surrounded on two sides by the walls of Building 5 and Building 7. It also sits somewhat under a nearby tree that could provide relief from heat through shade during the day. All of the climate modules in the parking lot are also likely measuring temperatures that could be influencing the hallways, classrooms, offices, and lab spaces directly adjacent to the parking lot in Buildings 1, 3, 5, and 7. See Figure 3-6 for parking lot climate module positioning details.

3.4.5 Pedestrian Pathway Beside Building 31

The exterior walkway between Building 31 and Building 13, sometimes referred to as “the Outfinite,” provides interesting information to measure as it is part of a major pedestrian walkway frequented by students, faculty, staff, and visitors alike. The walkway is lined on one side with Building 31 and another side with Building 13. It is composed of concrete pavers that runs parallel to a strip of soil and planted trees. Throughout the day, it can receive wind activity running parallel to the buildings which could alleviate heat that accumulates in the area. The tree planters also are a part of a sustainability effort, which makes this part of the walkway important to measure to see if this deliberate construction is also able to maintain a cooler temperature for the pedestrian traffic. The varied types of ground material also makes the walkway of interest to measure to observe whether or not the concrete pavers create a hotter environment or if the vegetation strip alleviates this compared to other parts of campus.

The first climate module in this area, as denoted by “O1,” was placed directly outside Building 17 on the pedestrian pathway through MIT’s campus. The O1 climate module is measuring asphalt material and is shielded on one side by the Building 17 wall. This climate module likely measures the temperatures experienced by a majority of passerby that use the pedestrian walkway due to its proximity to the main walking path and the branched path that leads to Vassar Street. The second climate module, as denoted by “O2,” was placed in the tree planter that runs parallel to the main pedestrian pathway. It is not exposed to direct sunlight due to the constant shade produced by the trees the climate module is placed in. It measures the soil material in the planter, and likely measures the temperature that those sitting on the adjacent benches experience. The last climate module, denoted as “O3,” was placed on concrete material near Building 13. It would experience shading from Building 13 as well as the nearby planter trees during the day. Although distanced from the walls of Building 13, the O3 climate module did stand next to a concrete column. Also within near proximity of a frequented bicycle rack, this climate module

(a) Climate modules denoted by O1, O2, and O3

(b) Contextual surroundings for O1

(c) O1 measuring asphalt surface material

(d) Contextual surroundings for O2

(e) O2 measuring vegetation surface material

(f) Contextual surroundings for O3

(g) O3 measuring concrete surface material

Figure 3-7: Placement of three (3) climate modules at the exterior walkway between Building 13 and Building 31 likely measures temperatures experienced by the bicycle rack users, as well as any bicycles subsequently parked for the day. See Figure 3-7 for pedestrian pathway climate module positioning details.

3.4.6 The Hive

The Hive Garden, also known as the Hive, is a community-oriented green space next to Walker Memorial built to increase sustainability education efforts on campus [37]. Visitors regularly spend time at the Hive to sit outside and enjoy outdoor activities. As a new green space on campus, it is vital to understand if it is conducive to outdoor use by those that frequent the campus. Located on the Saxon Lawn and situated near the Charles River, the Hive is composed mainly of grass with a small patch of fine gravel material that paves an area for a picnic bench and several hexagonal planters. Despite the large surface area of grass and vegetation, there are only a few trees that line the Saxon Lawn providing slight shade for the perimeter, but not for the majority of the area. As such, the Hive receives lots of direct solar radiation throughout the day without the relief of shade; however, the surfaces exposed to such heat are mostly grass and organic material that although have low albedo, also participate in evapotranspiration that helps to cool the surrounding air. Because the Hive is such a large and recent sustainability effort, it is important to measure the microclimate temperature of the area to see if it actually is conducive to outdoor activities or if the heat buildup is too intense for practical use.

The first climate module in this area, as denoted by “H1,” was placed directly adjacent to the lone picnic table at the Hive. It sits atop gravel material and measures the temperatures likely experienced by those that would use the picnic table. The H1 climate module does not experience shade during the day and is fairly distanced from the surrounding grass. It does not sit near any large structures and is exposed completely to wind activity. The second climate module, as denoted by “H2,” was placed in a creviced area near one of the larger hexagonal planters. It sat atop gravel material like the H1 climate module, but was surrounding on several sides by the wooden planter box as well as various plant materials. It experienced shading during

(a) Climate modules denoted by H1, H2, and H3

(b) Contextual surroundings for H1 (c) H1 measuring grass surface material

(d) Contextual surroundings for H2 (e) H2 measuring gravel surface material

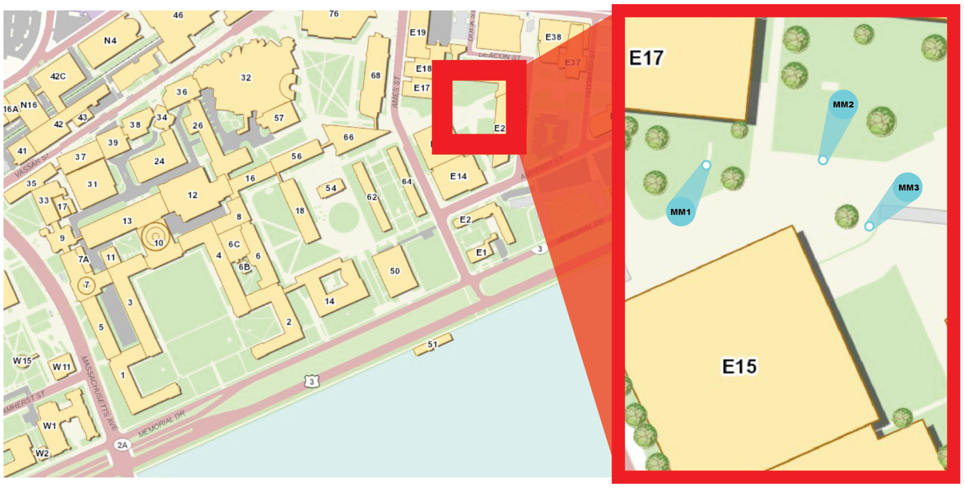
(f) Contextual surroundings for H3 (g) H3 measuring gravel surface material

Figure 3-8: Placement of three (3) climate modules at the Hive the day by the surrounding vegetation growing in the planter. Lastly, the third climate module, as denoted by "H3," was placed on the opposite side of the major planter that the H2 climate module was nestled in. The H3 climate module sat atop grass material and likely did not receive as much shading from the vegetation growing in the planter. It was also exposed somewhat to wind activity as well as water from periodic sprinkler waterings. See Figure 3-8 for The Hive climate module positioning details.

3.4.7 Courtyard Outside MIT Medical

The courtyard outside of MIT Medical is important to measure as a comparison with the new Welcome Center recently constructed on the opposite side of MIT Medical. Due to the calculated planning behind making the Welcome Center a community-oriented space, it is important to see how the older courtyard sitting adjacent to this Welcome Center compares in ground and ambient temperature. Since visitors will also flock to the Welcome Center as the entrance to MIT's campus, it is essential to discern if visitors will experience a disparity of temperature walking from the Welcome Center to the MIT Medical courtyard, which could in turn provide an unfortunate and dispiriting first impression. Not only will newcomers face these courtyard temperatures as one of their first MIT experiences, many existing students, staff, and faculty traverse this courtyard, sit within the greenspace, or travel and park bicycles. The area is composed of concrete pavers as well as large lawn sections that contain sprawling trees within. Bordered on the northeast side by the MIT Medical building and the southeast side by the List Arts Center, the area still experiences wind activity that can flow through the courtyard along the pedestrian pathways, which are designated by the concrete pavers. The trees and the buildings provide shade throughout the day for most of the perimeter, but most of the pedestrian walkway is not afforded much shade.

The first climate module in this area, denoted by "MM1," was placed on grass material sitting directly adjacent to a long wooden bench. It is completely exposed to wind activity, and also frequently shaded during the day by the trees overhead.



(a) Climate modules denoted by MM1, MM2, and MM3

(b) Contextual surroundings for MM1

(c) MM1 measuring grass surface material

(d) Contextual surroundings for MM2

(e) MM2 measuring paver surface material

(f) Contextual surroundings for MM3

(g) MM3 measuring paver surface material

Figure 3-9: Placement of three (3) climate modules at the courtyard outside MIT Medical

Though distanced from active pedestrian activity, it does likely measure the temperature experienced by those sitting by the bench or on the lawn for leisure activities. The second climate module, as denoted by “MM2,” was placed on paver material directly adjacent to a bench frequented by passerby. This area hosts a swathe of pavers while directly bordering a large grass lawn. The MM2 climate module likely experiences dappled shade during the day from the nearby trees and is exposed to all wind activity. Lastly, the third climate module, as denoted by “MM3,” was placed on concrete pavers in a bicycle parking area. It is shielded from wind activity on one side by a concrete wall, and it experiences brief shading by the nearby List Arts Center building. This climate module likely measures the temperature experienced by those that use the nearby bicycle racks as well as the bicycles parked at these racks for extended periods of time. See Figure 3-9 for the MIT Medical courtyard climate module positioning details.

3.4.8 Courtyard Outside Welcome Center

The recently constructed courtyard outside the MIT Welcome Center was built with the intention of creating a friendly public space for visitors to the MIT community [21]. It holds two acres of trees, planters, and sitting areas to allow the public to experience the coalescence of nature and city. Loosely bordered on two sides by the Welcome Center and the MIT Medical building, the space still allows for major wind activity. The grounds also include a mixture of surface material such as soil in the planters, wood planks in the staging and bench areas, and concrete in the walkway material. Like the Hive, because the Welcome Center was made as a space for people to commune and socialize, it is paramount that the temperature and humidity environment is favorable for those activities. It also represents the face of MIT for new visitors eager to explore the campus.

The first climate module in this area, denoted by “W1,” was placed on paver material situated directly next to a wooden bench that borders the southwestern end of a large planted area. It likely measures the temperature experienced by those that would use this particular bench as well as pedestrians walking through the open

(a) Climate modules denoted by W1, W2, and W3

(b) Contextual surroundings for W1

(c) W1 measuring paver surface material

(d) Contextual surroundings for W2

(e) W2 measuring vegetation surface material

(f) Contextual surroundings for W3

(g) W3 measuring wood surface material

Figure 3-10: Placement of three (3) climate modules at the Welcome Center courtyard. It is exposed to wind activity and does not receive shading from any structures or trees. The second climate module, as denoted by "W2," sits in the planted area adjacent to the W1 climate module and measures soil material below. It is partially surrounded by waist-high shrubs and vegetation. The climate module housing itself does not experience any shading from nearby structures, but the ground it measures would experience shading from the surrounding vegetation. Lastly, the third climate module, as denoted by "W3," was placed on the wooden stage area on the northwestern end of the same planter near the W1 and W2 climate modules. The W3 climate module does experience some shading from nearby trees and is partially elevated by about 12 inches due to the elevated nature of the stage. It is completely exposed to wind activity. It likely measures the temperature experienced by those that would use this wooden stage for a number of activities. See Figure 3-10 for the Welcome Center climate module positioning details.

Chapter 4

Results

Climate data (air temperature, ground temperature, relative humidity, and light) on MIT's campus was measured using the climate modules built for this research over three 24 hour periods: June 25, 2022; July 04, 2022; and July 06, 2022; with each day measured from 12:00am to 11:59pm. This data was then compared with the data collected from the Weather Underground stations.

4.1 Averages Per Day

The air temperature data for all climate modules and Weather Underground stations were collected and averaged per sensor for each of the three measured days: June 25 (see Figure 4-1); July 04 (see Figure 4-2); and July 06 (see Figure 4-3). The Weather Underground station averages are highlighted in yellow, while the climate module averages are highlighted in blue.

The highest average temperatures measured on June 25 included the O1 climate module at 83.90ºF, the P1 climate module at 81.56ºF, and the M2 climate module at 80.98ºF. The highest average temperatures measured on July 04 included the M2 climate module at 79.64ºF, the P1 climate module at 79.16ºF, and the M1 climate module at 78.90ºF. The highest average temperatures measured on July 06 included the M3 climate module at 81.43ºF, the P1 climate module at 80.67ºF, and the M2 climate module at 79.40ºF. The Weather Underground stations did not have average

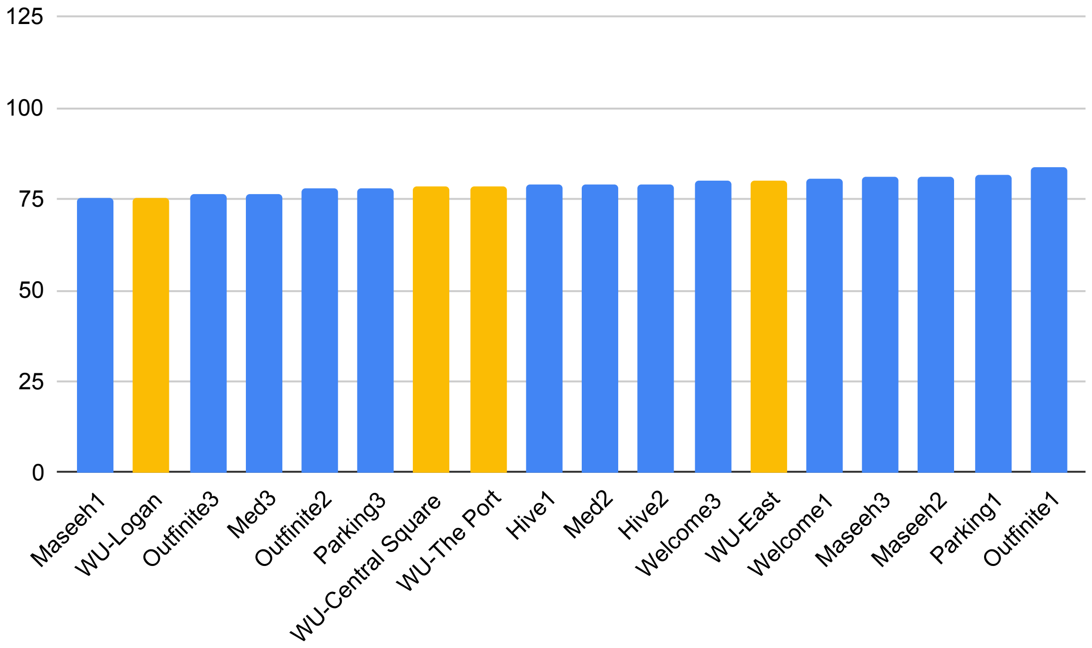


Figure 4-1: Average temperature of climate modules and Weather Underground stations for June 25

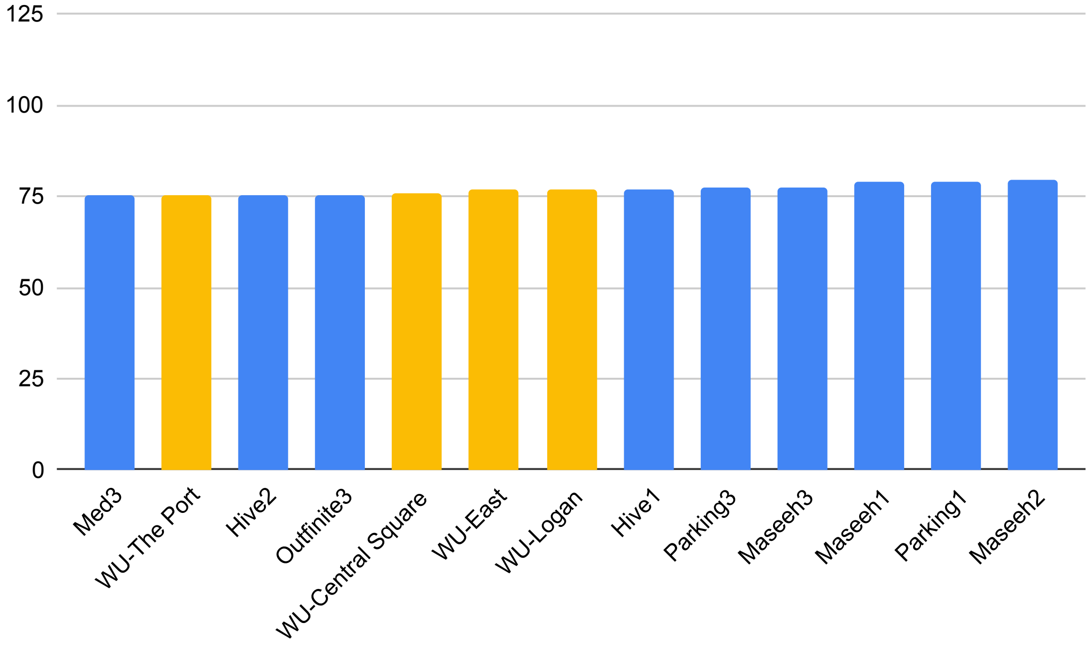


Figure 4-2: Average temperature of climate modules and Weather Underground stations for July 04

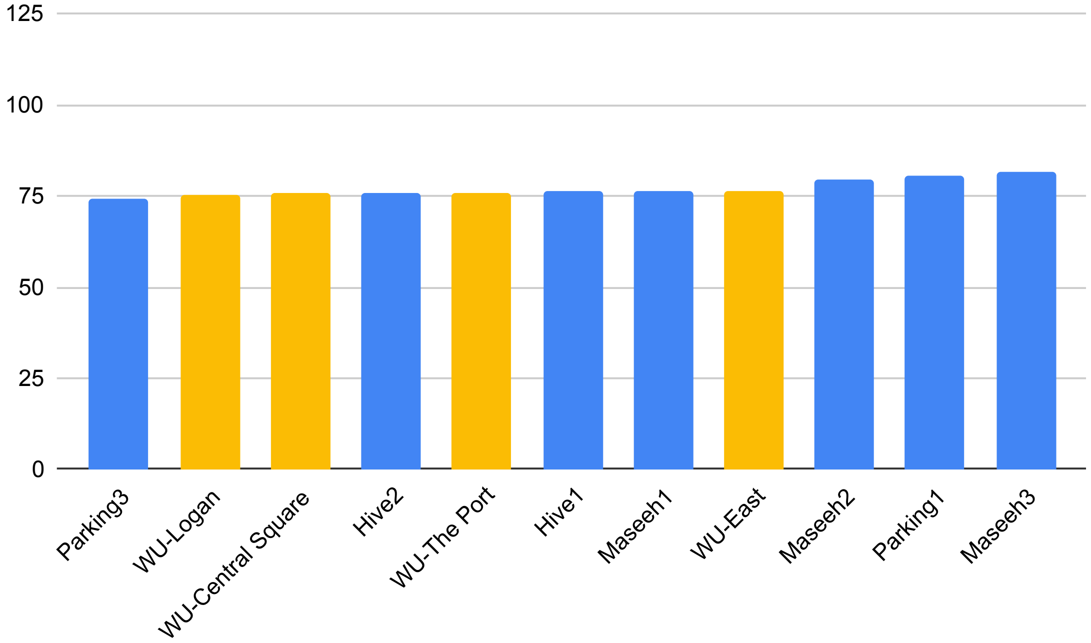


Figure 4-3: Average temperature of climate modules and Weather Underground stations for July 06

temperatures high enough to rank in the highest three average temperatures for any of the three days measured.

The lowest average temperatures measured on June 25 included the M1 climate module at 75.09ºF, the Boston Logan Airport Weather Underground station at 75.42ºF, and the O3 climate module at 76.34ºF. The lowest average temperatures measured on July 04 included the MM3 climate module at 75.05ºF, the Port Weather Underground station at 75.48ºF, and the H1 climate module at 75.51ºF. The lowest average temperatures measured on July 06 included the P3 climate module at 74.40ºF, the Boston Logan Airport Weather Underground station at 75.07ºF, and the Central Square Weather Underground station at 75.59ºF.

4.2 Highest Temperature Measured Per Day

The air temperature data for all climate modules and Weather Underground stations were collected and averaged per sensor for each of the three measured days: June

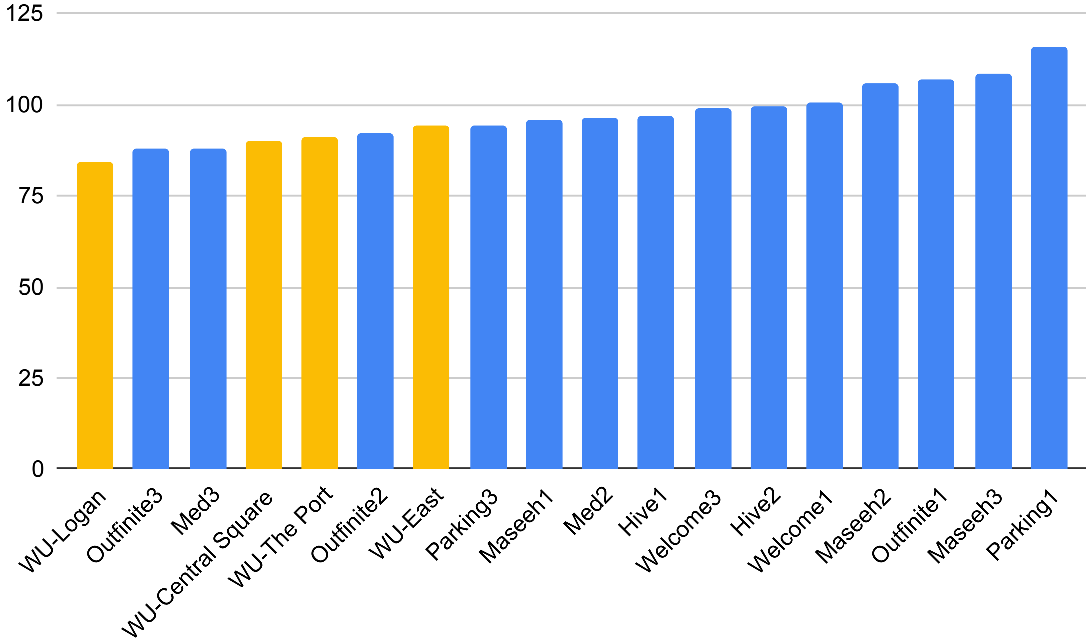


Figure 4-4: Highest measured temperature of climate modules and Weather Underground stations for June 25

25 (see Figure 4-4); July 04 (see Figure 4-5); and July 06 (see Figure 4-6). The Weather Underground station averages are highlighted in yellow, while the climate module averages are highlighted in blue. The climate modules that recorded the highest temperature measurements were those in the parking lot beside Building 3, the pedestrian walkway beside Building 31, and consistently in the Maseeh courtyard.

The highest temperatures measured on June 25 included the O1 climate module at 106.76°F, the M3 climate module at 108.76°F, and the P1 climate module at 116.06°F. The highest average temperature measured on July 04 included the P1 climate module at 107.89°F, the M2 climate module at 107.46°F, and the M1 climate module at 107.36°F. The highest average temperature measured on July 06 included the M3 climate module at 118.59°F, the P1 climate module at 115.92°F, and the M2 climate module at 103.16°F. The Weather Underground stations did not have highest temperatures measured high enough to rank in the top three highest measured temperatures for any of the three days measured.

The bottom three highest temperatures measured on June 25 included the M1

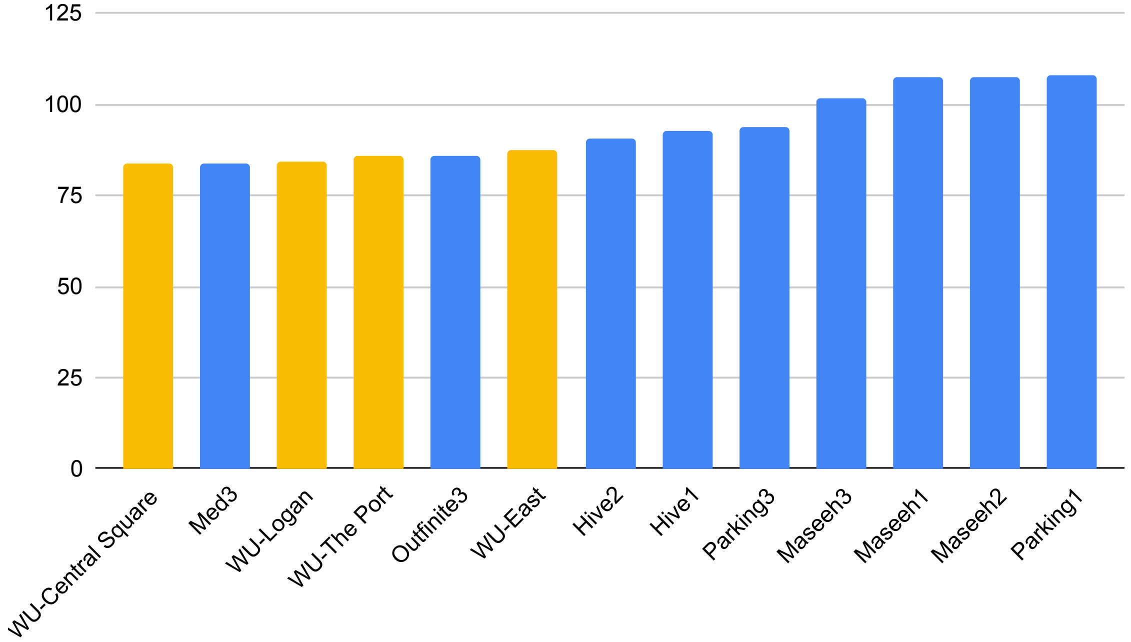


Figure 4-5: Highest measured temperature of climate modules and Weather Underground stations for July 04

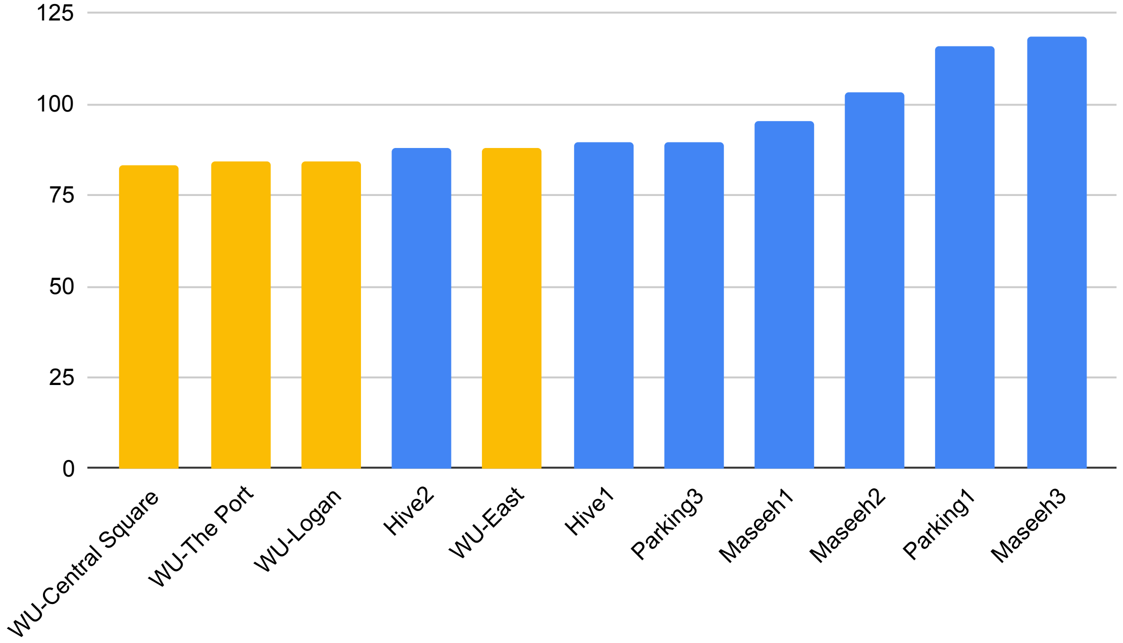


Figure 4-6: Highest measured temperature of climate modules and Weather Underground stations for July 06

climate module at 75.09ºF, the Boston Logan Airport Weather Underground station at 75.42ºF, and the O3 climate module at 76.34ºF. The bottom three highest temperatures measured on July 04 included the MM3 climate module at 75.05ºF, the Port Weather Underground station at 75.48ºF, and the H1 climate module at 75.51ºF. The bottom three highest temperatures measured on July 06 included the Central Square Weather Underground station at 83.30ºF, the Port Weather Underground station at 84.00ºF, and the Boston Logan Airport Weather Underground station also at 84.00ºF.

For each of the three days measured, the averages for all climate modules and Weather Underground stations had temperature swings of 8.81ºF on June 25, 4.59ºF on July 04, and 7.04ºF on July 06. These temperature swings are also around the 75ºF temperature range. This is consistent over the three days, and the Weather Underground station averages are generally reporting averages amongst the climate module sensors, trending somewhat in the lower half. However, when compared to the highest measured temperature for each climate module and Weather Underground station over the three measured days, the swing in temperature difference widens to 32ºF on June 25, 24ºF on July 04, and 35.29ºF on July 06.

4.3 Comparisons of Temperature Measurements Per Day

The air temperature data for the three climate modules that measured the highest air temperature for the three measured days (see Figures 4-4, 4-5, and 4-6) as well as all of the Weather Underground stations were collected over a 24 hour period for three non-consecutive days: June 25 (see Figure 4-7); July 04 (see Figure 4-8); and July 06 (see Figure 4-9). The climate modules are indicated by the red, blue, and yellow lines in each of the figures, and the Weather Underground stations are indicated by the green, orange, turquoise, and aqua lines. The Weather Underground stations all follow a similar arcing pattern throughout the day while the climate modules on

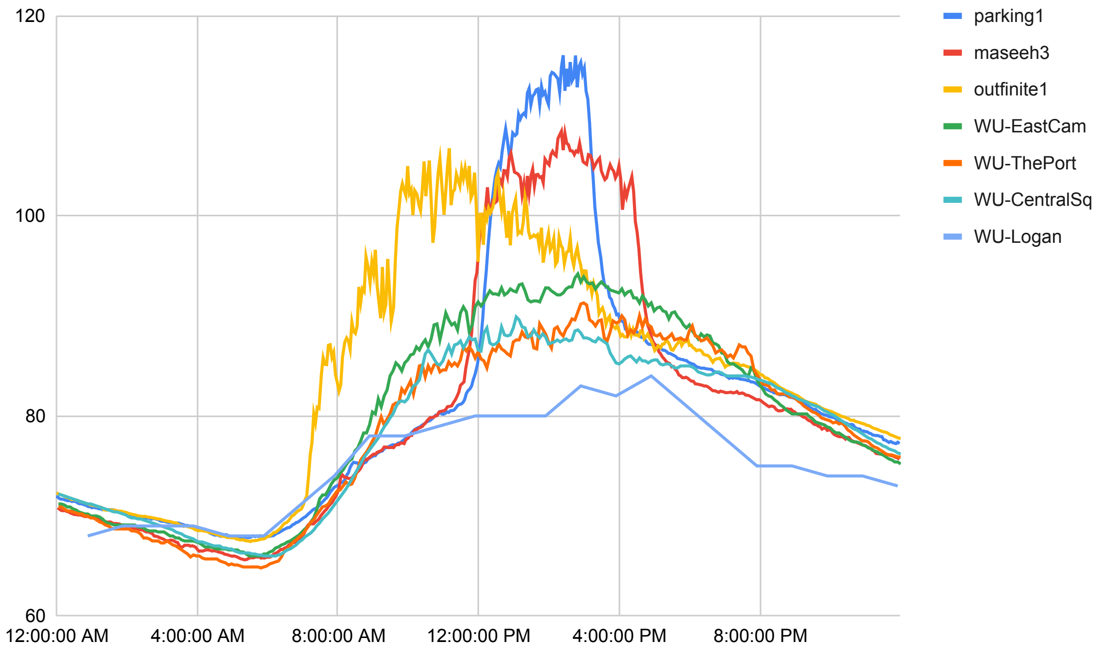


Figure 4-7: Air temperature measured over a 24-hour period for June 25 for climate modules and Weather Underground stations

campus follow a higher arc.

4.4 Environmental Data Per Climate Module Per Day

From the data collected for the highest measured temperature for the three days measured, the climate modules that recorded the top three temperature measurements were further explored. For each of the top three temperature ranking climate modules for June 25, July 04, and July 06, the light exposure, air temperature, ground temperature, and real feel temperature difference was graphed over a 24 hour period (see FIGURE 4-10, 4-11, 4-12, 4-13, 4-14, 4-15, 4-16, 4-17, and 4-18). The combination of temperature and relative humidity measured results in a different temperature realistically experienced from the measured temperature, due to varying levels of humidity. The actual, or real feel, temperature was calculated for each climate module over the

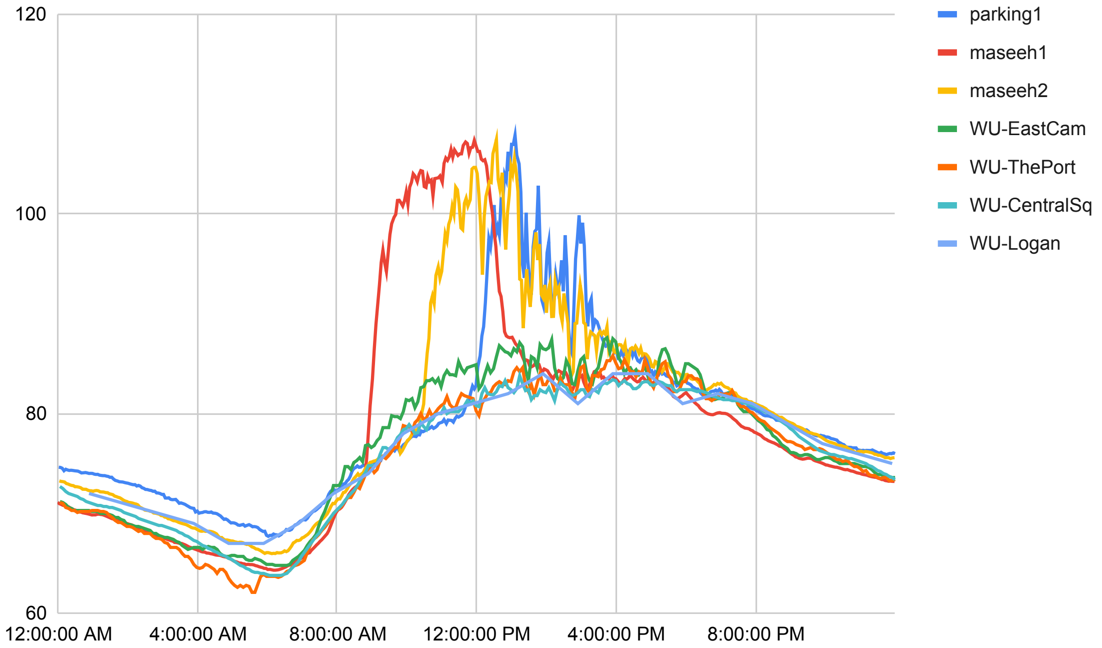


Figure 4-8: Air temperature measured over a 24-hour period for July 04 for climate modules and Weather Underground stations

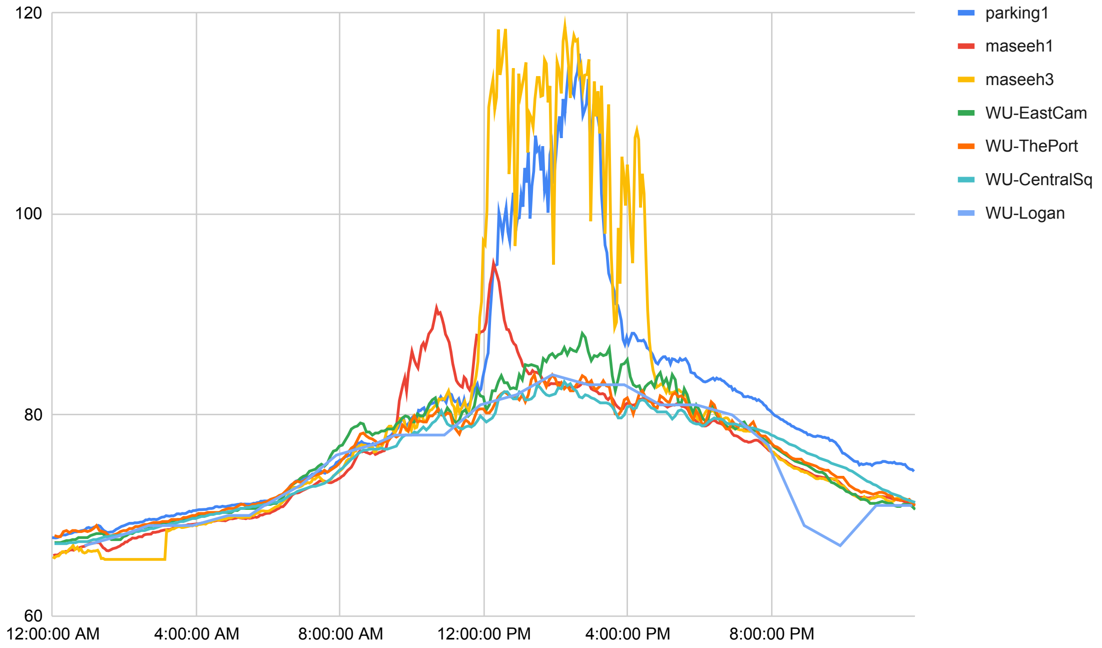


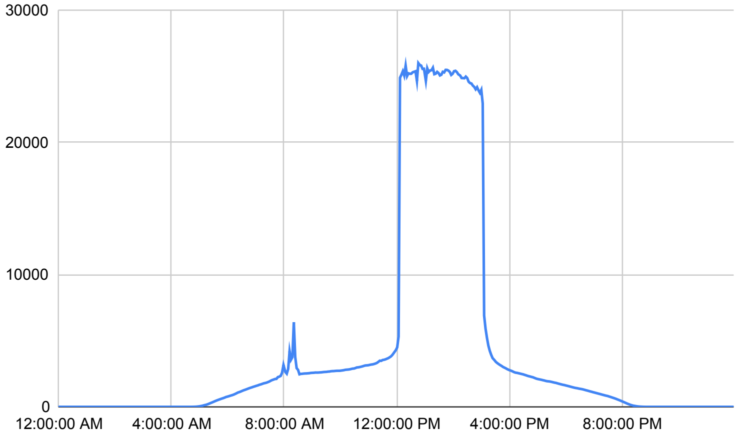
Figure 4-9: Air temperature measured over a 24-hour period for July 06 for climate modules and Weather Underground stations

24 hour period for the three days measured and then the difference was taken between this calculated real feel temperature and the climate module measured temperature.

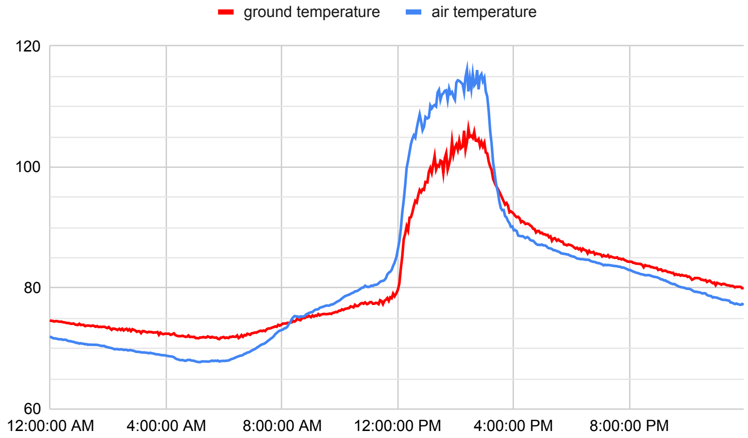
4.4.1 June 25 Climate Module Measurements

For June 25, the three climate modules that measured the highest temperatures included P1, M3, and O1, in order of highest to lowest. The P1 climate module recorded heightened 25,000 lux measurements between 12:00pm and 3:15pm. This indicates an illuminance between ambient sunlight and direct sunlight [5]. The sharp increase at 12:00pm and the sharp decrease at 3:15pm would indicate that the sensor experienced direct sunlight between these times, only to be covered by shade prior and after this window. See Figure 4-10a for P1 climate module light measurements. The P1 climate module measured an increase in air and ground temperature between 12:00pm and 3:15pm. The climate module measured higher air temperatures than ground temperatures for the 3.25 hour time period. The average ground temperature measured between 12:00pm and 3:15pm is 98.86$^{\underline{o}}$F and the average air temperature measured for the same time period is 108.81$^{\underline{o}}$F, 10$^{\underline{o}}$F higher than the average ground temperature. See Figure 4-10b for P1 climate module air and ground temperature measurements. The P1 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:50am, 12:00pm to 3:15pm, and 9:09pm to 11:59pm. The P1 climate module then experienced real feel temperatures lower than the measured temperatures from 10:50am to 12:00pm, and 3:15pm to 9:09pm. The P1 climate module experienced on average temperatures 2.07$^{\underline{o}}$F higher than the measured temperature during the 24 hour period. See Figure 4-10c for P1 climate module real feel temperature difference measurements.

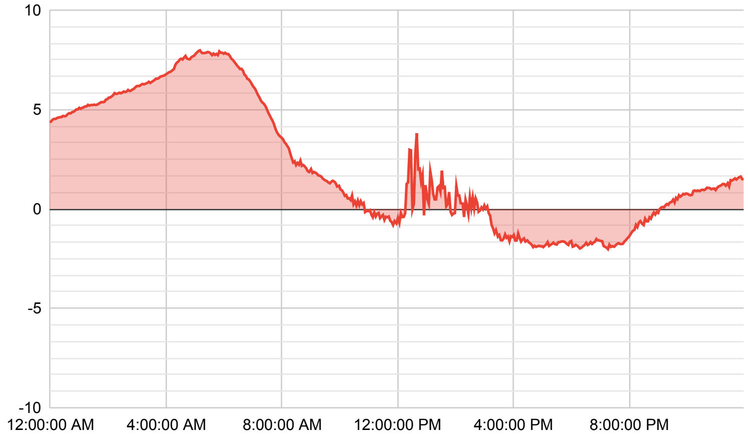
The M3 climate module recorded an average of 21,000 lux measurements between 11:48am and 4:39pm. This indicates an illuminance of high ambient sunlight [5]. The sharp increase at 11:48am and the sharp decrease at 4:39pm would indicate that the sensor experienced a large amount of ambient light, if not direct sunlight between these times, only to be covered by shade prior and after this window. See Figure 4-11a for M3 climate module light measurements. The M3 climate module measured



(a) Light measurements for the P1 climate module over the June 25 time period



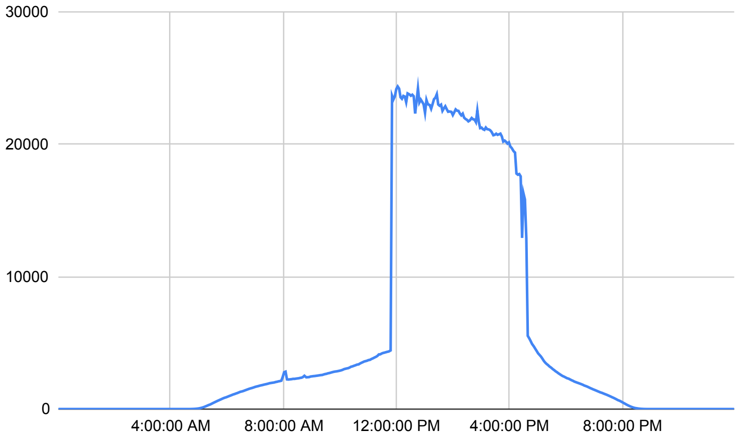
(b) Air and ground temperature for the P1 climate module over the June 25 time period



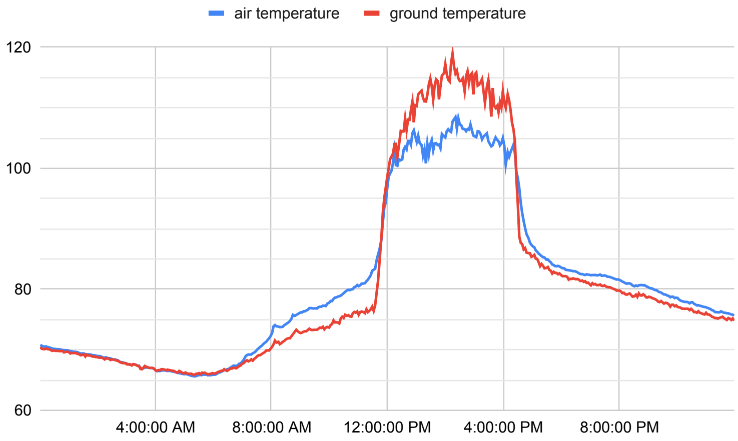
(c) Real feel temperature difference for the P1 climate module over the June 25 time period

Figure 4-10: Climate data for the the P1 climate module over the June 25 time period an increase in air and ground temperature between 11:48am and 4:39pm. The climate module measured higher air temperatures than ground temperatures for the 4.85 hour time period. The average ground temperature measured between 11:48am and 4:39pm is 109.46ºF and the average air temperature measured for the same time period is 103.30ºF, 6ºF lower than the average ground temperature. See Figure 4-11b for M3 climate module air and ground temperature measurements. The M3 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:55am, 11:57am to 4:15pm, and 8:24pm to 11:59pm. The M3 climate module then experienced real feel temperatures lower than the measured temperatures from 10:55am to 11:57am, and 4:15pm to 8:24pm. The M3 climate module experienced on average temperatures 2.90ºF higher than the measured temperature during the 24 hour period. See Figure 4-11c for M3 climate module real feel temperature difference measurements.

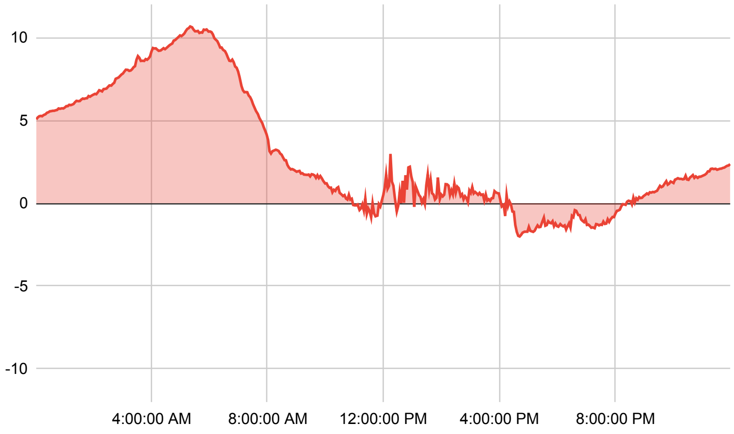
Lastly, the O1 climate module recorded an average of 21,000 lux measurements between 7:04am and 3:19pm. This indicates an illuminance of high ambient sunlight [5]. The somewhat stark but arced increase at 7:04am and the sharp decrease at 3:19pm would indicate that the sensor experienced a strong transition to ambient sunlight starting at 7:04am and was covered by shade after this window. See Figure 4-12a for O1 climate module light measurements. The O1 climate module measured more modest arcs of air and ground temperature increase for the 8.25 hour time period between 7:04 am and 3:19pm. The climate module measured higher air temperature than ground temperature between 7:04am and 12:14pm, which subsequently switched and measured higher ground temperature than air temperature between 12:14pm and 3:19pm. The average ground temperature measured between 7:04am and 12:14pm is 91.39ºF and the average air temperature measured for the same time period is 94.87ºF, 3.5ºF higher than the average ground temperature. During the 12:14pm to 3:19pm time period, the average ground temperature measured was 104.11ºF while the average air temperature measured was 97.74ºF, 6.5ºF lower than the average ground temperature for the same time period. See Figure 4-12b for O1 climate module air and ground temperature measurements. The O1 climate



(a) Light measurements for the M3 climate module over the June 25 time period



(b) Air and ground temperature for the M3 climate module over the June 25 time period



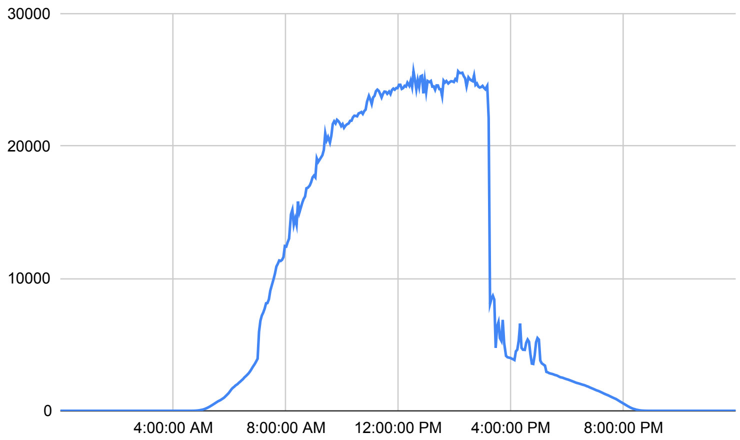
(c) Real feel temperature difference for the M3 climate module over the June 25 time period

Figure 4-11: Climate data for the the M3 climate module over the June 25 time period module experienced real feel temperatures higher than the measured temperatures from 12:00am to 3:43pm and 8:27pm to 11:59pm. The O1 climate module then experienced real feel temperatures lower than the measured temperatures from 3:43pm to 8:27pm. The O1 climate module experienced on average temperatures 2.47ºF higher than the measured temperature during the 24 hour period. See Figure 4-12c for O1 climate module real feel temperature difference measurements.

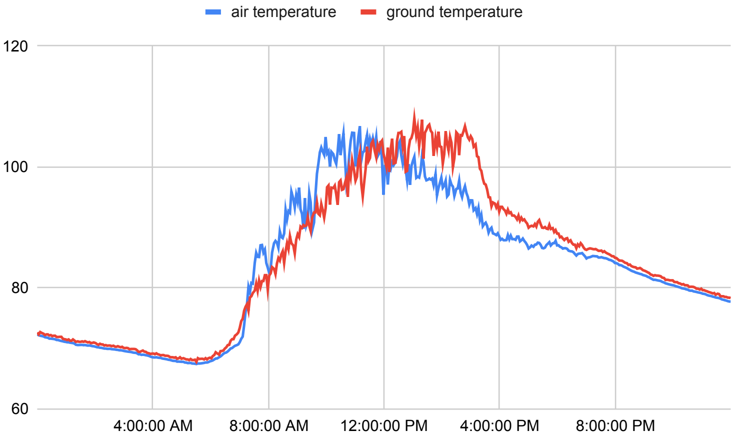
4.4.2 July 04 Climate Module Measurements

For July 04, the three climate modules that measured the highest temperatures included P1, M2, and M1, in order of highest to lowest. The P1 climate module recorded heightened but vacillating lux measurements between 12:06pm and 3:05pm. This time period measured an average of 19,000 lux, which indicates an illuminance of strong ambient sunlight with inconsistent shade interference [5]. See Figure 4-13a for P1 climate module light measurements. The P1 climate module measured an increase in air and ground temperature at 10:32am through 1:14pm where it began a constant decline until the end of the measured day. The climate module measured somewhat higher air temperatures than ground temperatures for the 2.70 hour time period. The average ground temperature measured between 10:32am through 1:14pm is 94.35ºF and the average air temperature measured for the same time period is 99.45ºF, 5.10ºF higher than the average ground temperature. See Figure 4-13b for P1 climate module air and ground temperature measurements. The P1 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:16am and 9:33pm to 11:59pm. The P1 climate module then experienced real feel temperatures lower than the measured temperatures from 10:16am to 9:33pm. The P1 climate module experienced on average temperatures 0.76ºF higher than the measured temperature during the 24 hour period. See Figure 4-13c for P1 climate module real feel temperature difference measurements.

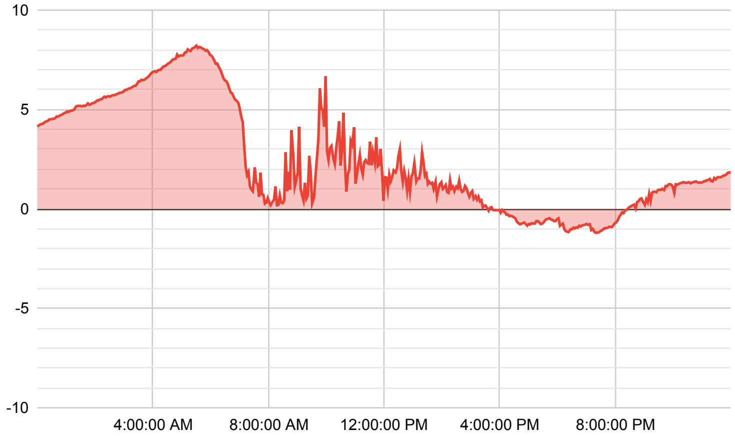
The M2 climate module recorded heightened but vacillating lux measurements between 10:23am and 3:50pm. This time period measured an average of 16,000 lux, which indicates an illuminance of medium ambient sunlight with inconsistent shade



(a) Light measurements for the O1 climate module over the June 25 time period

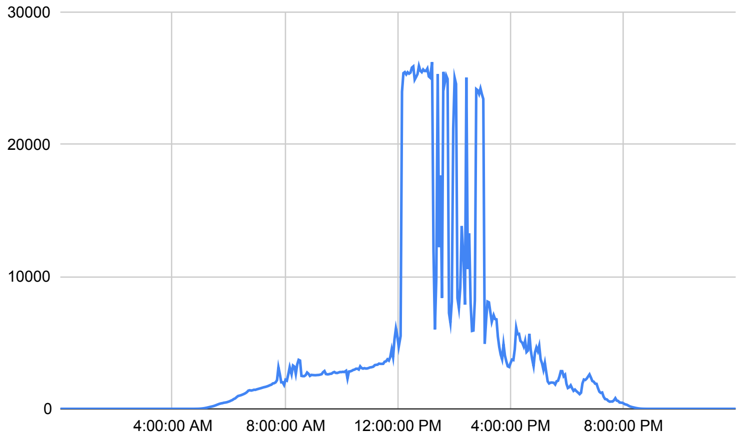


(b) Air and ground temperature for the O1 climate module over the June 25 time period

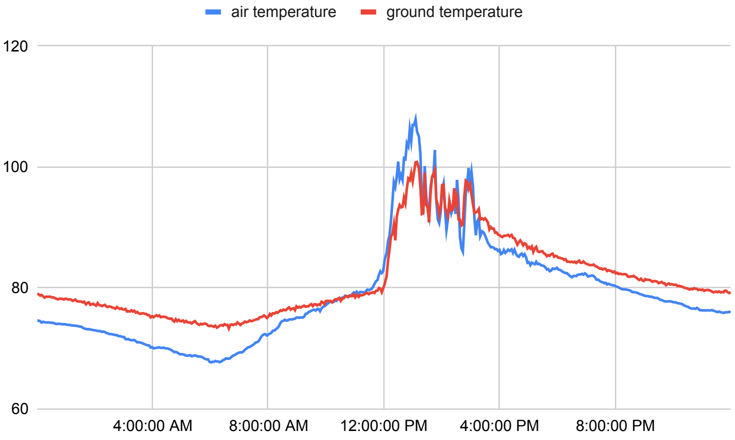


(c) Real feel temperature difference for the O1 climate module over the June 25 time period

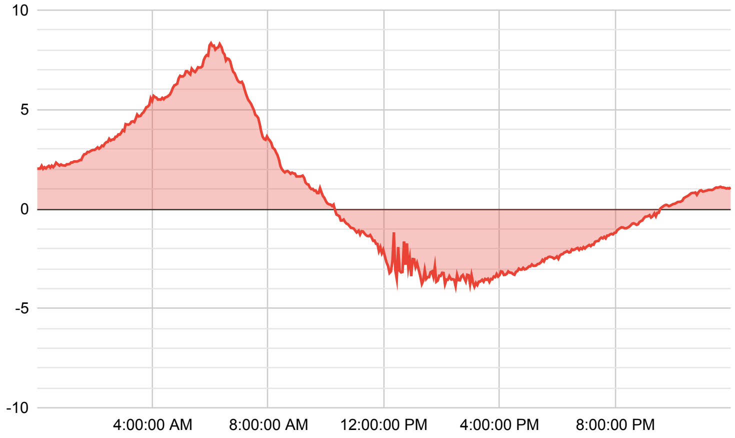
Figure 4-12: Climate data for the the O1 climate module over the June 25 time period



(a) Light measurements for the P1 climate module over the July 04 time period



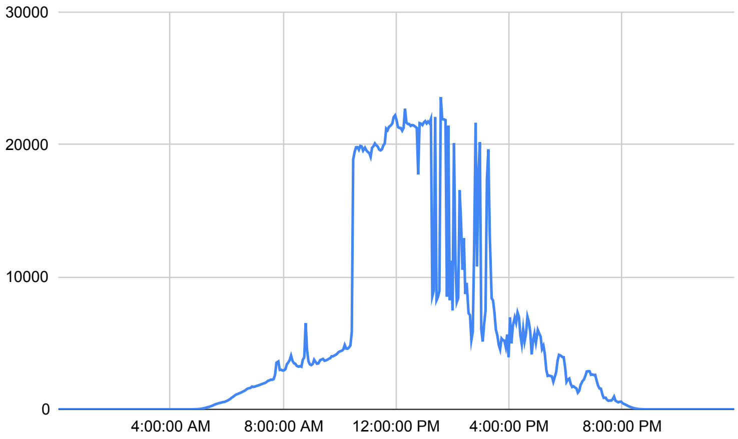
(b) Air and ground temperature for the P1 climate module over the July 04 time period



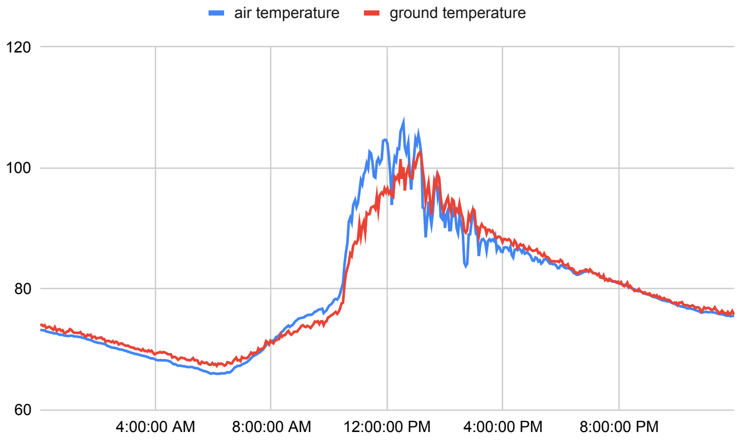
(c) Real feel temperature difference for the P1 climate module over the July 04 time period

Figure 4-13: Climate data for the the P1 climate module over the July 04 time period interference [5]. See Figure 4-14a for M2 climate module light measurements. The M2 climate module measured increases in air and ground temperature between 12:06pm and 3:05pm. The climate module measured somewhat higher air temperatures than ground temperatures for the 2.98 hour time period. The average ground temperature measured between 12:06pm and 3:05pm is 94.19^{o}F and the average air temperature measured for the same time period is 96.50^{o}F, 2.31^{o}F higher than the average ground temperature. See Figure 4-14b for M2 climate module air and ground temperature measurements. The M2 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:17am and 9:12pm to 11:59pm. The M2 climate module then experienced real feel temperatures lower than the measured temperatures from 10:17am to 9:12pm. The M2 climate module experienced on average temperatures 1.62^{o}F higher than the measured temperature during the 24 hour period. See Figure 4-14c for M2 climate module real feel temperature difference measurements.

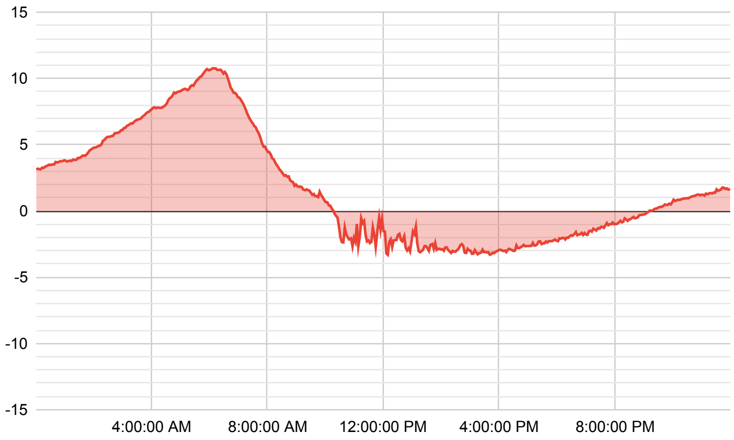
Lastly, the M1 climate module recorded an average of 19,000 lux measurements between 8:45am and 12:20pm. This indicates an illuminance of medium ambient sunlight [5]. The sharp increase at 8:45am and the sharp decrease at 12:20pm would indicate that the sensor experienced a quick transition to ambient sunlight starting at 8:45am and was covered by shade after this window at 12:20pm. See Figure 4-15a for M1 climate module light measurements. The M1 climate module measured an increase in air and ground temperature for the 3.58 hour time period between 8:45am and 12:20pm. The average ground temperature measured between 8:45am and 12:20pm is 98.78^{o}F and the average air temperature measured for the same time period is 100.39^{o}F, 1.61^{o}F higher than the average ground temperature. See Figure 4-15b for M1 climate module air and ground temperature measurements. The M1 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:18am and 8:12pm to 11:59pm. The M1 climate module then experienced real feel temperatures lower than the measured temperatures from 10:18pm to 8:12pm. The M1 climate module experienced on average temperatures 2.80^{o}F higher than the measured temperature during the 24 hour period. See Figure



(a) Light measurements for the M2 climate module over the July 04 time period



(b) Air and ground temperature for the M2 climate module over the July 04 time period



(c) Real feel temperature difference for the M2 climate module over the July 04 time period

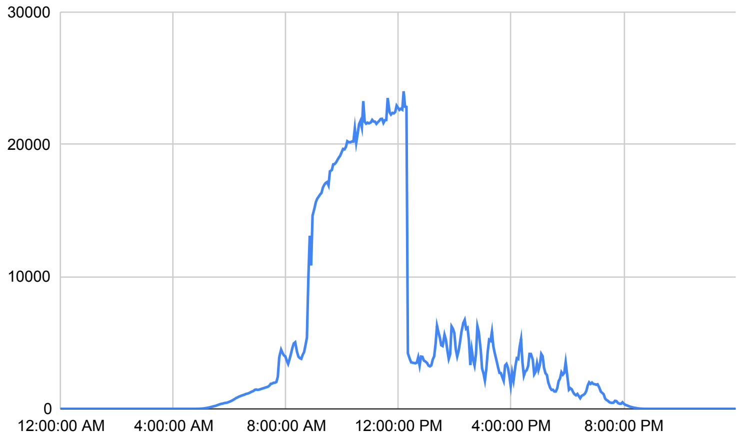
Figure 4-14: Climate data for the the M2 climate module over the July 04 time period

4-15c for M1 climate module real feel temperature difference measurements.

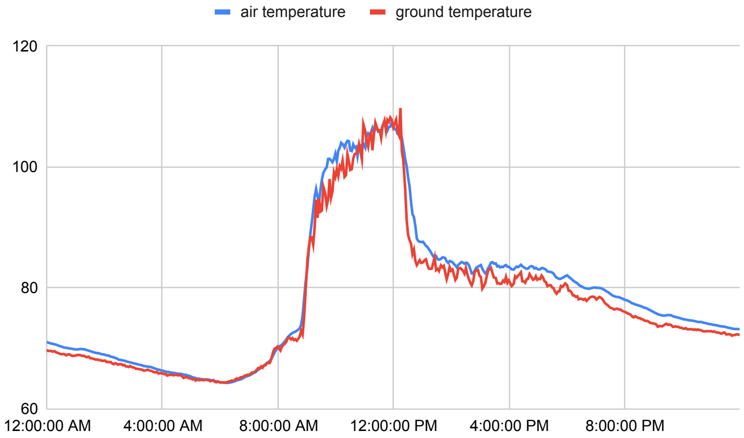
4.4.3 July 06 Climate Module Measurements

For July 06, the three climate modules that measured the highest temperatures included M3, P1, and M2 in order of highest to lowest. The M3 climate module recorded low light levels throughout the 24 hour time period. The small increase in light levels occurred from 11:56am to 4:30pm and measured an average of 700 lux. This indicates an illuminance of overcast daylight [5]. See Figure 4-16a for M3 climate module light measurements. The M3 climate module measured an increase in air and ground temperature at 11:50am through 4:36pm. The climate module measured higher air temperatures than ground temperatures for the 4.77 hour time period. The average ground temperature measured between 11:50am and 4:36pm is 84.99°F and the average air temperature measured for the same time period is 107.29°F, 22.30°F higher than the average ground temperature. See Figure 4-16b for M3 climate module air and ground temperature measurements. The M3 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 3:22pm, 3:53pm to 4:18pm, and 5:44pm to 11:59pm. The M3 climate module then experienced real feel temperatures lower than the measured temperatures from 3:22pm to 3:53pm and 4:18pm to 5:44pm. The M3 climate module experienced on average temperatures 3.32°F higher than the measured temperature during the 24 hour period. See Figure 4-16c for M3 climate module real feel temperature difference measurements.

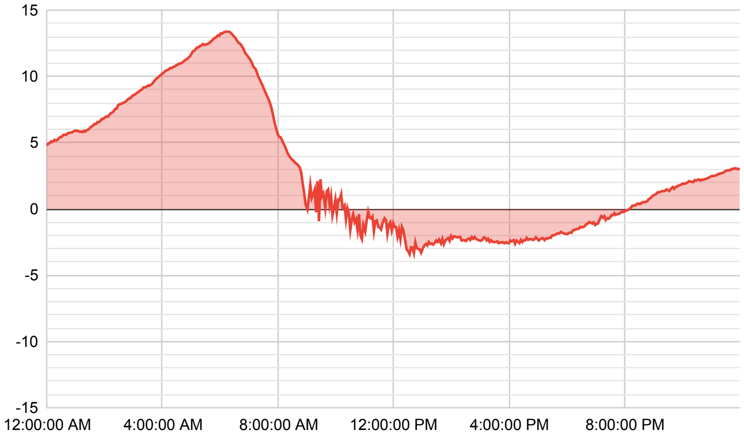
The P1 climate module recorded an average of 23,000 lux measurements between 12:04am and 3:13pm. This indicates an illuminance of strong ambient sunlight [5]. The sharp increase at 12:04pm and the sharp decrease at 3:13pm would indicate that the sensor experienced a quick transition to ambient sunlight starting at 12:04pm and was covered by shade after this window at 3:13pm. See Figure 4-17a for P1 climate module light measurements. The P1 climate module measured an increase in air and ground temperature for the 3.40 hour time period between 12:10pm and 3:34pm. The average ground temperature measured between 12:10pm and 3:34pm is 97.57°F and the average air temperature measured for the same time period is



(a) Light measurements for the M1 climate module over the July 04 time period

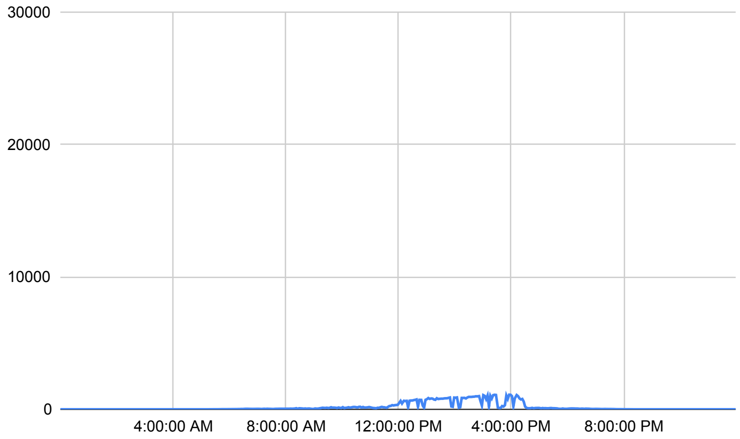


(b) Air and ground temperature for the M1 climate module over the July 04 time period

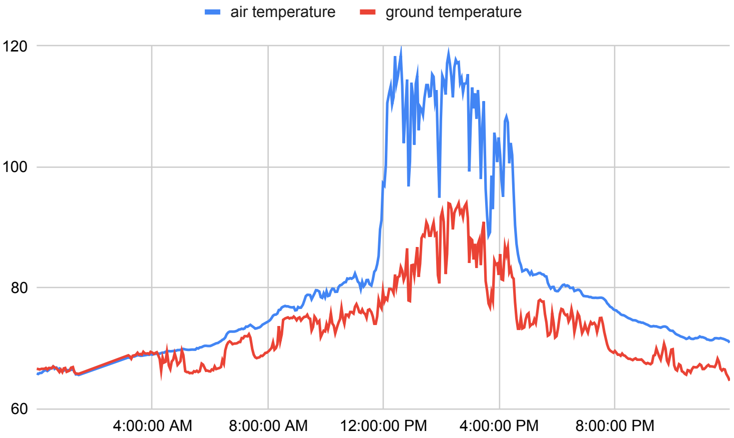


(c) Real feel temperature difference for the M1 climate module over the July 04 time period

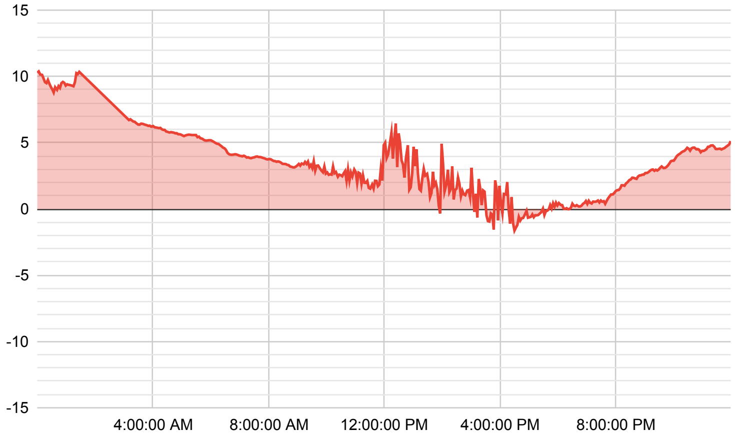
Figure 4-15: Climate data for the the M1 climate module over the July 04 time period



(a) Light measurements for the M3 climate module over the July 06 time period



(b) Air and ground temperature for the M3 climate module over the July 06 time period

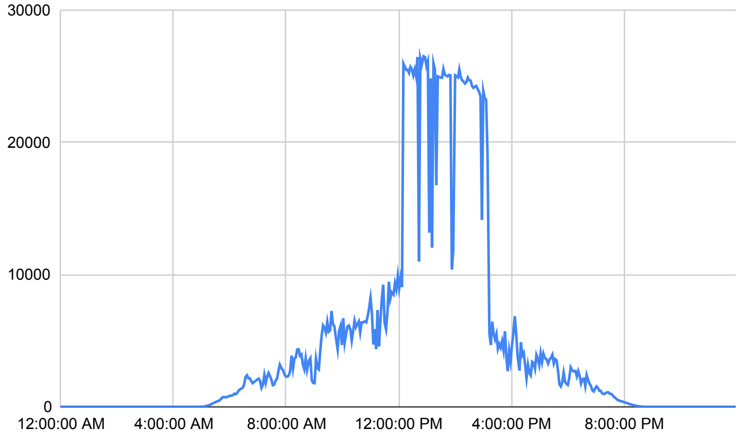


(c) Real feel temperature difference for the M3 climate module over the July 06 time period

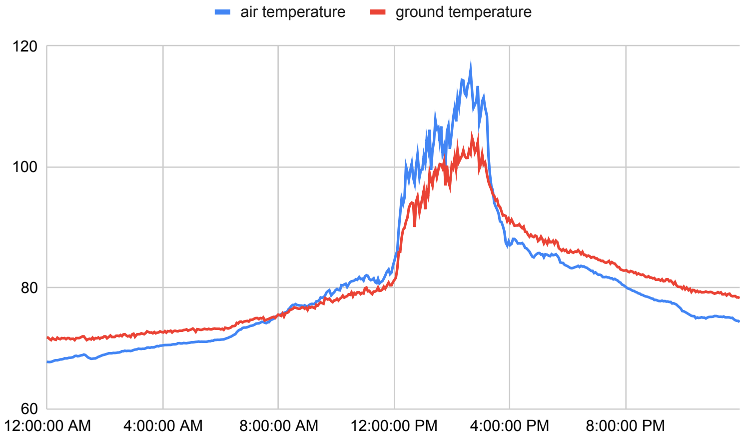
Figure 4-16: Climate data for the the M3 climate module over the July 06 time period

104.17ºF, 6.60ºF higher than the average ground temperature. See Figure 4-17b for P1 climate module air and ground temperature measurements. The P1 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 3:00pm and 8:33pm to 11:59pm. The P1 climate module then experienced real feel temperatures lower than the measured temperatures from 3:00pm to 8:33pm. The P1 climate module experienced on average temperatures 2.43ºF higher than the measured temperature during the 24 hour period. See Figure 4-17c for P1 climate module real feel temperature difference measurements.

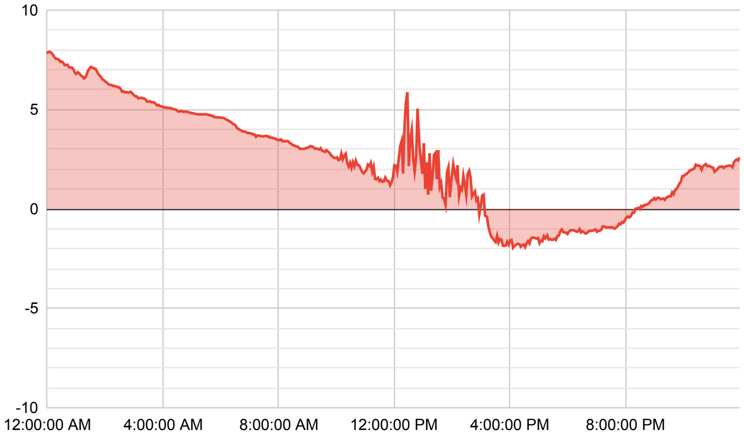
Lastly, the M2 climate module recorded heightened but vacillating lux measurements between 11:36am and 3:28pm. This time period measured an average of 18,000 lux, which indicates an illuminance of medium ambient [5]. See Figure 4-18a for M2 climate module light measurements. The M2 climate module measured an increase in air and ground temperature between 11:42pm and 3:35pm. The climate module measured somewhat higher air temperatures than ground temperatures for the 3.88 hour time period. The average ground temperature measured between 11:42pm and 3:35pm is 93.60ºF and the average air temperature measured for the same time period is 96.25ºF, 2.65ºF higher than the average ground temperature. See Figure 4-18b for M2 climate module air and ground temperature measurements. The M2 climate module experienced real feel temperatures higher than the measured temperatures from 12:00am to 3:10pm and 7:18pm to 11:59pm. The M2 climate module then experienced real feel temperatures lower than the measured temperatures from 3:10pm to 7:18pm. The M2 climate module experienced on average temperatures 2.97ºF higher than the measured temperature during the 24 hour period. See Figure 4-18c for M2 climate module real feel temperature difference measurements.



(a) Light measurements for the P1 climate module over the July 06 time period

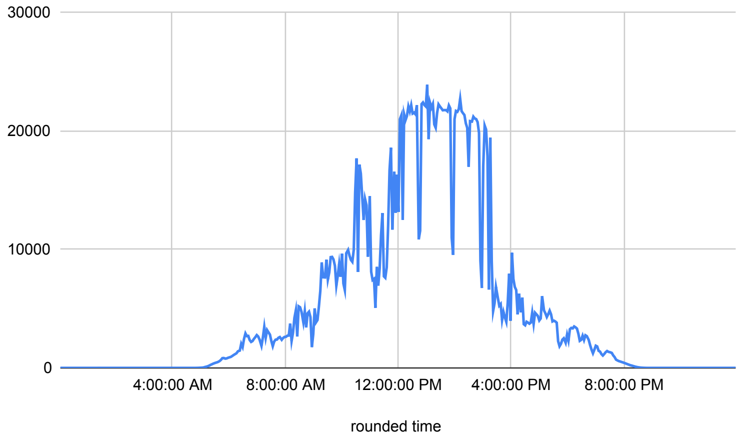


(b) Air and ground temperature for the P1 climate module over the July 06 time period

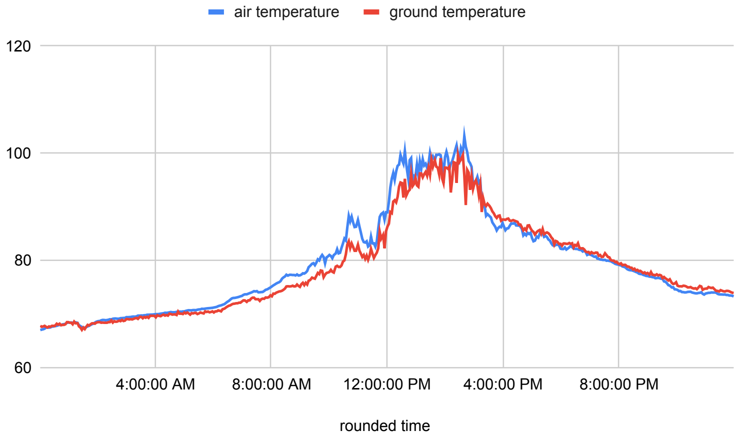


(c) Real feel temperature difference for the P1 climate module over the July 06 time period

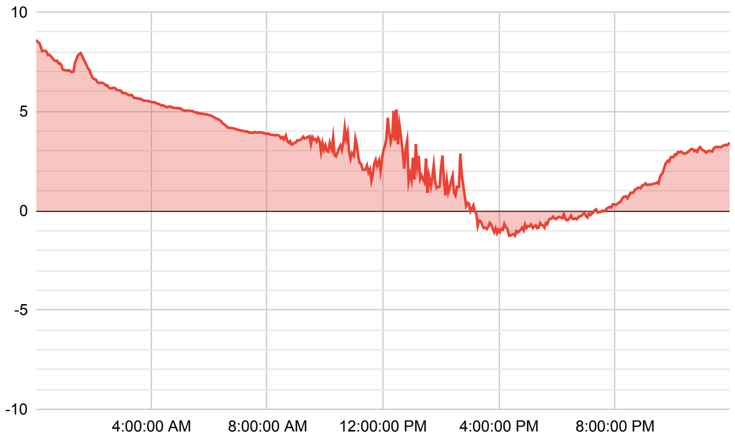
Figure 4-17: Climate data for the the P1 climate module over the July 06 time period



(a) Light measurements for the M2 climate module over the July 06 time period



(b) Air and ground temperature for the M2 climate module over the July 06 time period



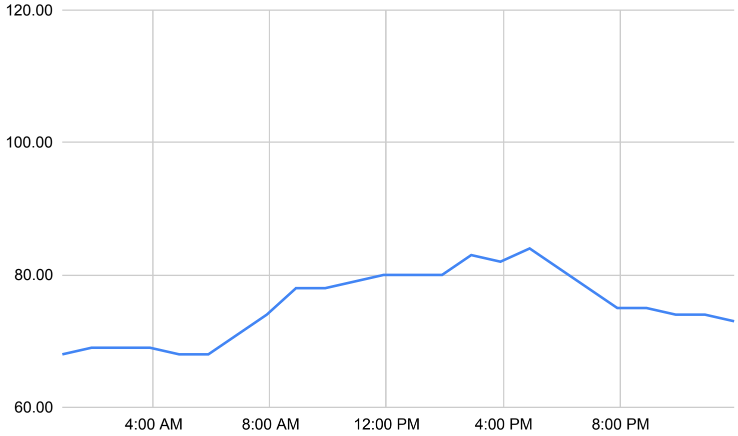
(c) Real feel temperature difference for the M2 climate module over the July 06 time period

Figure 4-18: Climate data for the the M2 climate module over the July 06 time period

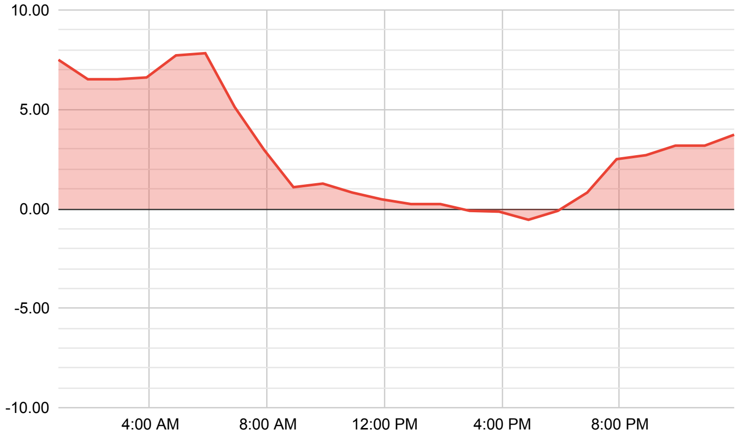
4.5 Environmental Data Per Weather Underground Station

The air temperature data for the Boston Logan Airport, East Cambridge, the Port, and the Central Square Weather Underground stations were mapped over a 24-hour period for June 25. The difference between the real feel temperature, calculated through the temperature and humidity data for each Weather Underground station, and the measured temperature was also mapped over the 24-hour period. For the Boston Logan Airport Weather Underground station, the temperature began a temperature arc at 5:54am. For the East Cambridge Weather Underground station, the temperature began a temperature arc at 6:04am. For the Port Weather Underground station, the temperature began a temperature arc at 6:09am. And for the Central Square Weather Underground station, the temperature began a temperature arc at 6:34am. All Weather Underground stations reached a maximum temperature and then consistently decreased into the end of the 24-hour measuring period. The Boston Logan Airport Weather Underground station reached the maximum temperature of 84.00ºF at 4:54pm. The East Cambridge Weather Underground station reached the maximum temperature of 94.20ºF at 2:49pm. The Port Weather Underground station reached the maximum temperature of 91.30ºF at 2:59pm. And the Central Square Weather Underground station reached the maximum temperature of 89.90ºF at 1:04pm. See Figure 4-19a, 4-20a, 4-21a, and 4-22a for air temperature data for all Weather Underground stations.

The Boston Logan Airport Weather Underground station experienced real feel temperatures higher than the measured temperatures from 12:00am to 1:54pm and 5:54pm to 11:59pm. The station then experienced real feel temperatures lower than the measured temperatures from 1:54pm to 5:54pm. The station experienced on average temperatures 2.92ºF higher than the measured temperature during the 24 hour period. The East Cambridge Weather Underground station experienced real feel temperatures higher than the measured temperatures from 12:00am to 5:39pm and 8:09pm to 11:59pm. The station then experienced real feel temperatures lower than

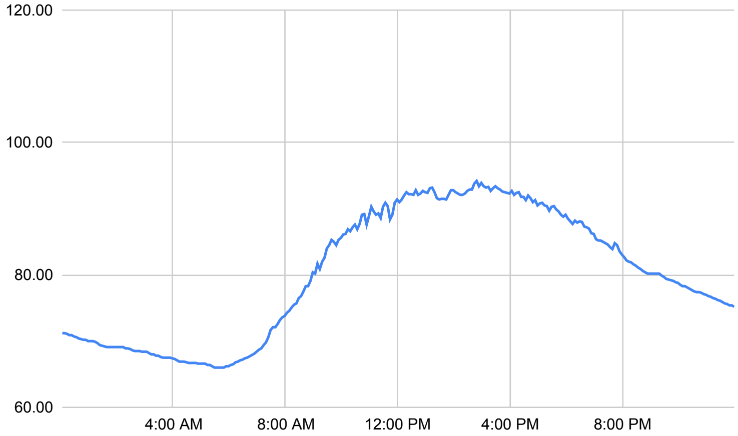


(a) Air temperature for the Boston Logan Airport Weather Underground station over the June 25 time period

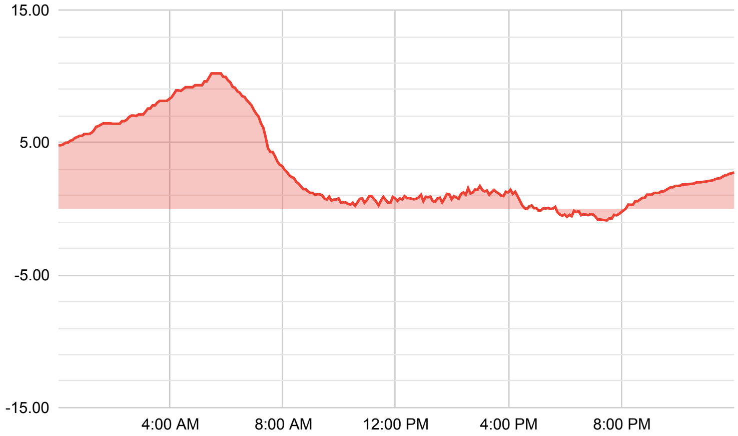


(b) Real feel temperature difference for the Boston Logan Airport Weather Underground station over the June 25 time period

Figure 4-19: Climate data for the Boston Logan Airport Weather Underground station over the June 25 time period



(a) Air temperature for the East Cambridge Weather Underground station over the June 25 time period

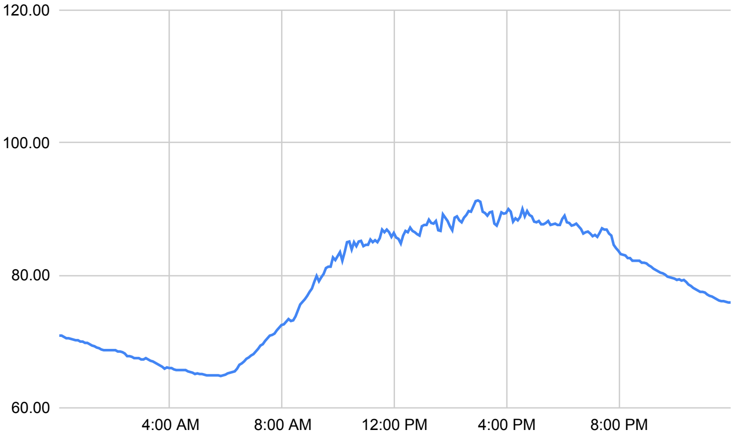


(b) Real feel temperature difference for the East Cambridge Weather Underground station over the June 25 time period

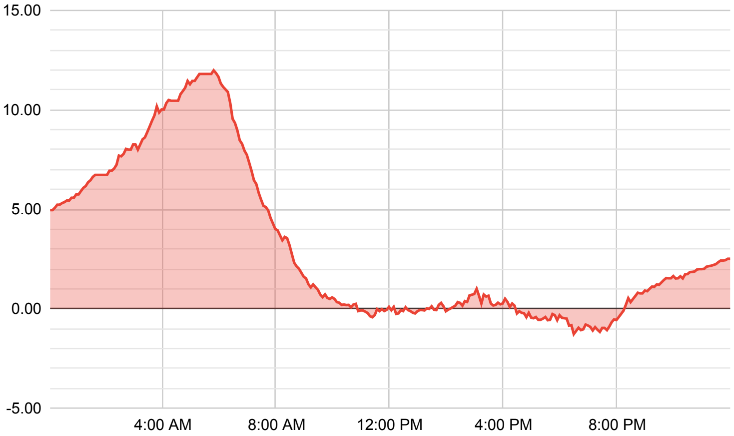
Figure 4-20: Climate data for the East Cambridge Weather Underground station over the June 25 time period the measured temperatures from 5:39pm to 8:09pm. The station experienced on average temperatures 3.01ºF higher than the measured temperature during the 24 hour period. The Port Weather Underground station experienced real feel temperatures higher than the measured temperatures from 12:00am to 10:49am, 2:09pm to 4:24pm, and 8:19pm to 11:59pm. The station then experienced real feel temperatures lower than the measured temperatures from 10:49am to 2:09pm and 4:24pm to 8:19pm. The station experienced on average temperatures 3.07ºF higher than the measured temperature during the 24 hour period. Lastly, the Central Square Weather Underground station experienced real feel temperatures higher than the measured temperatures from 12:00am to 5:59pm and 8:19pm to 11:59pm. The station then experienced real feel temperatures lower than the measured temperatures from 5:59pm to 8:19pm. The station experienced on average temperatures 2.98ºF higher than the measured temperature during the 24 hour period. See Figure 4-19b, 4-20b, 4-21b, and 4-22b for real feel temperature difference data for all Weather Underground stations.

4.6 Air Temperatures Measured Above 80ºF, 90ºF, and 100ºF

For June 25, the P1, M3, and O1 climate modules recorded the highest air temperatures. The P1 climate module measured 7.28 hours above 80ºF, 0.87 hours above 90ºF, and 2.93 hours above 100ºF, for a total of 11.08 hours at 80ºF or higher. The M3 climate module measured 7.28 hours above 80ºF, 0.87 hours above 90ºF, and 2.93 hours above 100ºF, for a total of 11.08 hours at 80ºF or higher. The O1 climate module measured 7.85 hours above 80ºF, 3.8 hours above 90ºF, and 3.12 hours above 100ºF, for a total of 14.77 hours at 80ºF or higher. The Boston Logan Airport Weather Underground station measured 6.00 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 6.00 hours at 80ºF or higher. The East Cambridge Weather Underground station measured 6.45 hours above 80ºF, 5.88 hours above 90ºF, and 0 hours above 100ºF, for a total of 12.33 hours at 80ºF or higher. The Port

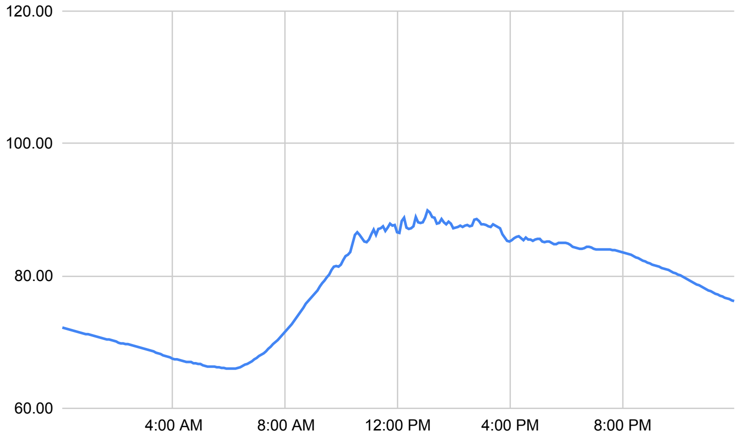


(a) Air temperature for the Port Weather Underground station over the June 25 time period

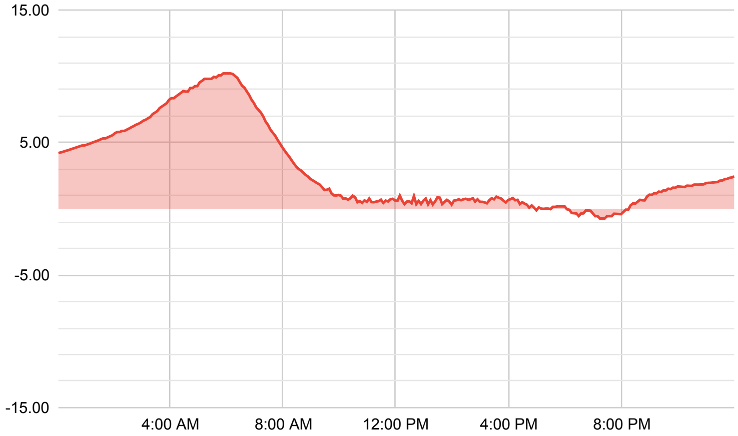


(b) Real feel temperature difference for the Port Weather Underground station over the June 25 time period

Figure 4-21: Climate data for the Port Weather Underground station over the June 25 time period



(a) Air temperature for the Central Square Weather Underground station over the June 25 time period



(b) Real feel temperature difference for the Central Square Weather Underground station over the June 25 time period

Figure 4-22: Climate data for the Central Square Weather Underground station over the June 25 time period

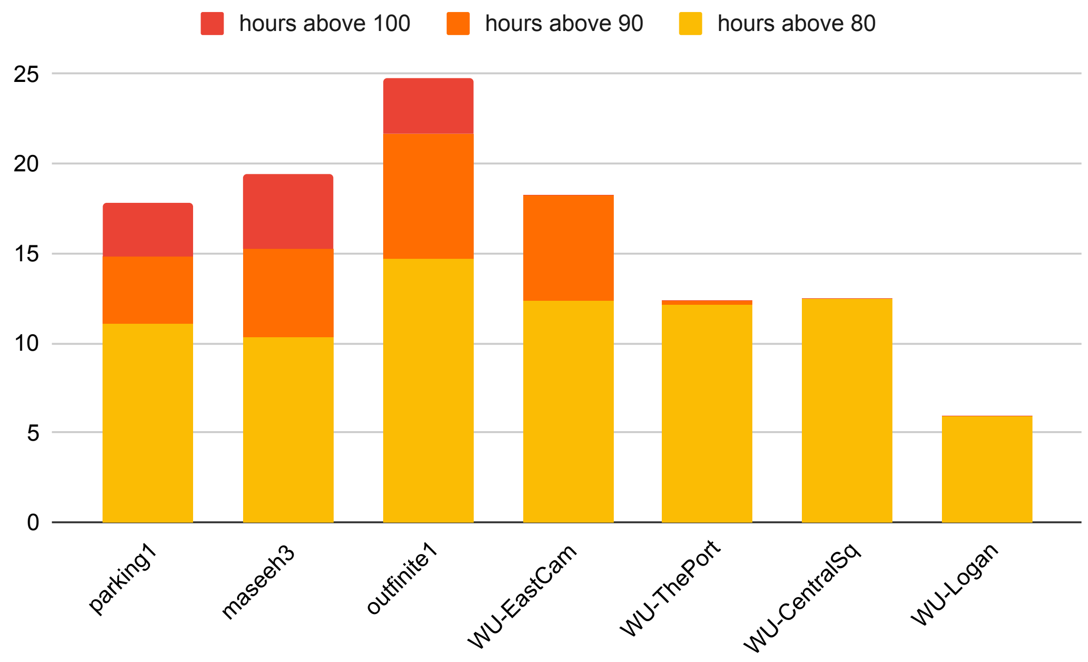


Figure 4-23: Time measured from the P1, M3, and O1 climate modules and Weather Underground stations above 80ºF, 90ºF, and 100ºF for June 25

Weather Underground station measured 11.92 hours above 80ºF, 0.25 hours above 90ºF, and 0 hours above 100ºF, for a total of 12.17 hours at 80ºF or higher. The Central Square Weather Underground station measured 12.50 hours above 80ºF, 0 hours above 90ºF and 100ºF, for a total of 12.50 hours at 80ºF or higher. See Figure 4-23 for time measured above 80ºF, 90ºF, and 100ºF for June 25.

For July 04, the P1, M1, and M2 climate modules recorded the highest air temperatures. The P1 climate module measured 5.50 hours above 80ºF, 2.21 hours above 90ºF, and 0.77 hours above 100ºF, for a total of 8.48 hours at 80ºF or higher. The M1 climate module measured 6.34 hours above 80ºF, 0.86 hours above 90ºF, and 2.67 hours above 100ºF, for a total of 9.87 hours at 80ºF or higher. The M2 climate module measured 6.44 hours above 80ºF, 2.39 hours above 90ºF, and 1.22 hours above 100ºF, for a total of 10.05 hours at 80ºF or higher. The Boston Logan Airport Weather Underground station measured 9.00 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 9.00 hours at 80ºF or higher. The East Cambridge Weather Underground station measured 9.82 hours above 80ºF, 0.10 hours above

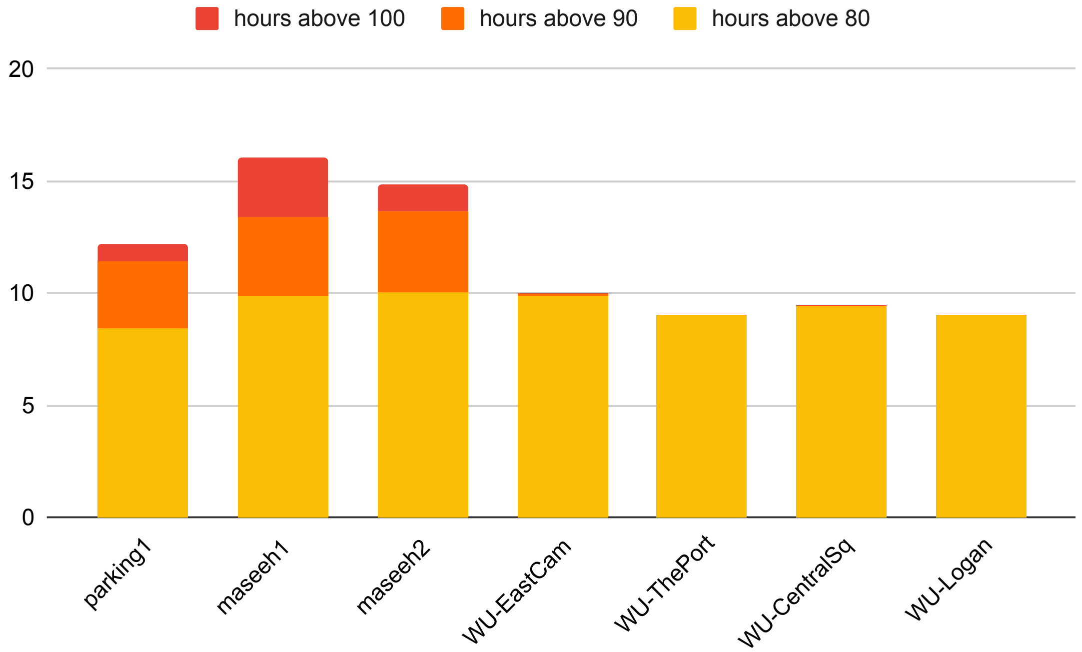


Figure 4-24: Time measured from the P1, M1, and M2 climate modules and Weather Underground stations above 80ºF, 90ºF, and 100ºF for July 04

90ºF, and 0 hours above 100ºF, for a total of 9.92 hours at 80ºF or higher. The Port Weather Underground station measured 9.01 hours above 80ºF, 0 hours above 90ºF and 100ºF, for a total of 9.01 hours at 80ºF or higher. The Central Square Weather Underground station measured 9.50 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 9.50 hours at 80ºF or higher. See Figure 4-24 for time measured above 80ºF, 90ºF, and 100ºF for July 04.

And lastly, for July 06, the P1, M1, and M3 climate modules recorded the highest air temperatures. The P1 climate module measured 6.30 hours above 80ºF, 1.17 hours above 90ºF, and 2.38 hours above 100ºF, for a total of 9.85 hours at 80ºF or higher. The M1 climate module measured 7.57 hours above 80ºF, 0.50 hours above 90ºF, and 0 hours above 100ºF, for a total of 8.07 hours at 80ºF or higher. The M3 climate module measured 3.38 hours above 80ºF, 1.09 hours above 90ºF, and 3.38 hours above 100ºF, for a total of 7.85 hours at 80ºF or higher. The Boston Logan Airport Weather Underground station measured 7.00 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 9.00 hours at 80ºF or higher. The East Cambridge Weather

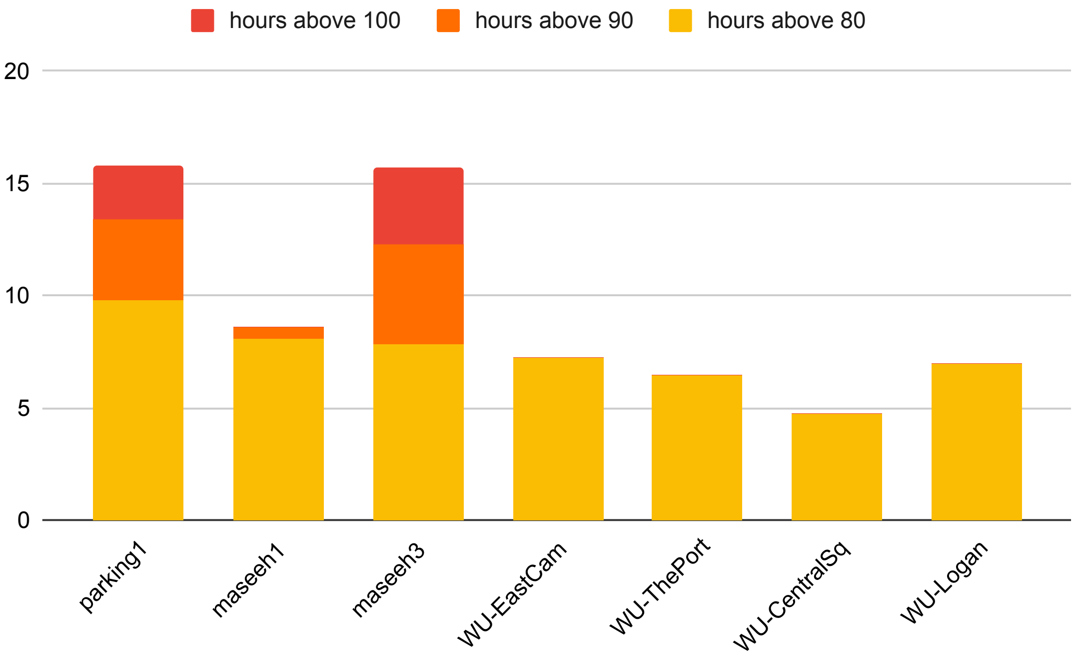


Figure 4-25: Time measured from the P1, M1, and M3 climate modules and Weather Underground stations above 80ºF, 90ºF, and 100ºF for July 06

Underground station measured 7.22 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 7.22 hours at 80ºF or higher. The Port Weather Underground station measured 6.47 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 6.47 hours at 80ºF or higher. The Central Square Weather Underground station measured 4.80 hours above 80ºF and 0 hours above 90ºF and 100ºF, for a total of 9.50 hours at 80ºF or higher. See Figure 4-25 for time measured above 80ºF, 90ºF, and 100ºF for July 06.

Chapter 5

Discussion

5.1 Findings

These highest measured temperature ranges are 4 to 5 times the average temperature ranges for the same days. This means that the weather and heat forecast being evaluated from the Weather Underground stations may be comparable to areas on MIT in the field of averages, but practically, various campus areas at MIT could be experiencing highs 4 to 5 times higher above the average than is being reported. Although the comparable averages imply that the areas on campus that experience very high temperature measurements also experience very low temperature measurements to even out the average, it does not diminish the fact that those highs experienced can have added detrimental effects as they occur.

It is important to note that the areas that measured the highest temperature on campus all experience heavy pedestrian traffic in one form or another. The parking lot adjacent to Building 3, specifically the northeastern corner, is situated next to an active loading dock. This would mean that when official weather sources are reporting a high of 84ºF, those that are physically loading and unloading materials in the parking lot would also be doing this in 116ºF, conditions that are beyond likely to cause heat exhaustion or heat stroke after extended periods of time. This area would so act as an easy escape for any air conditioning circulating through the building, which wastes energy and financial resources. As heat rises from this corner, it can also negatively impact any offices or classrooms on the upper levels of Building 3, which could also interfere with student education and research unless adequately combatted with increased air conditioning, which in turn would mean expending more energy and financial resources. The pedestrian walkway measuring 106ºF on a reportedly 84ºF day would likely deter pedestrians from this major outdoor walkway. The Maseeh courtyard would also likely deter students from spending time in the area simply because temperatures are too high, such as seeing 108ºF on this theoretical 84ºF day. In fact, it would be to the detriment of students' health to be outside in the courtyard at these temperatures. Student rooms facing the courtyard would not be able to open their windows to cool down their rooms, for the heat emanating from the courtyard would most likely heat up their rooms. Furthermore, because individual student rooms do not have air conditioning, students would be unable to cool their rooms unless using a third party air conditioning unit or propping doors open to circulate the air conditioned air from the hallway into rooms.

It is also of note that the averages (seen in Figures 4-1, 4-2, and 4-3) implied that the high temperatures experienced in areas like the Maseeh courtyard, the pedestrian walkway between Building 13 and Building 31, as well as the parking lot between Building 3 and Building 5 would also mean lower temperatures in those areas to even out the average temperatures measured with the Weather Underground stations, the actual temperature felt is shown to be increased in the nighttime hours, between 8:00pm and 8:00am. This means that the relief felt at night may not include temperatures as low as previously measured when accounting for the relative humidity. Without this nightly relief, people can be exposed to unrelenting heightened temperatures that can result in health ailments like heat exhaustion and even heat stroke. These three days measured were also typical summer temperatures for Cambridge, not heat wave temperatures, which could also indicate that in truly extreme heat as experienced in heat waves, the temperatures experienced in these high heat areas (the Maseeh courtyard, the Building 13 pedestrian walkway, and the Building 3 parking lot) could be even higher and for extended periods of time.

After seeing the measurements from six different areas on MIT's campus, it is demonstrated that temperature and humidity in microclimates can vary significantly even during the same day and time. It is especially important to note the Boston Logan Airport reported the lowest three temperatures measured over June 25, July 04, and July 05. As such, organizations like ASHRAE that provide the standards for the HVAC industry in the greater Boston area that also garner their from the Boston Logan International Airport should reconsider their current methods. One point of data for 48.4 square miles of varying terrain and material may be misrepresenting the actual temperatures experienced across Cambridge, which may mean that the buildings and structures currently being constructed are not following a relevant building code for the surrounding environment. Given additional data points, these standards may very well differ among the towns, neighborhoods, and even houses for the greater Boston area, which could suggest added granularity to building codes for various areas around the city. Temperature measurement should likewise occur at a smaller scale than the current Weather Underground measurements in order to capture a temperature profile more authentic to the diverse areas in Cambridge.

Furthermore, across 24-hour time periods, the Weather Underground stations mirrored each other in the type of temperature arcs throughout the day for all three days measured. The campus climate modules, however, exhibited heightened and unrelated heat paths throughout the day. Especially on June 25, the pedestrian pathway began experiencing higher temperatures than the nearby Weather Underground stations starting as early as 7:10am, while the parking lot began seeing higher temperatures starting in midday, at 12:10pm. The Maseeh courtyard also began heating up at 12:10pm but retained the heat for a longer period of time than the parking lot. Following the Weather Underground station data, these campus heat signatures would not be easily predicted.

There are even different heat signatures within the same campus area being measured. The Maseeh courtyard, which reported some of the highest temperatures for all three days measured, does not experience temperature uniformly. On July 04, the M1 climate module began measuring a drastic temperature increase at 8:54am, while the M2 climate module began measuring a similar temperature hike at 10:32am. Due to the climate module positions in the courtyard, it is likely that the M1 climate module was initially exposed to sunlight while the M2 climate module still stood in the shade. As the sun rises from east to west, it would directly shine onto the M1 climate module first, which stood on the western end, then the M2 climate module, which stood in the center, and finally the M3 climate module, which stood in the eastern end of the courtyard. The Maseeh building would act as shading for some climate modules as the sun rises and sets. This explanation is also supported with the July 06 data where the M1 climate module measures a steep temperature increase at 9:36am, while the M3 climate module reports a sharp temperature rise at 11:50am.

In addition to the heightened temperatures measured on campus during the midday hours, the real feel temperature calculated from the relative humidity in the air shows a large increase in the actual temperature experienced in the first half of the day over all the climate module readings as well as the Weather Underground station measurements. This increase seen in the morning hours counteracts the dip in temperature also seen in the 24-hour periods during those same morning times. As a result, these morning measured temperatures that revolve around the 70ºF range are raised to levels more like 75ºF and even 80ºF. Moreover, the already heightened midday temperatures also see a boost in heat from the real feel temperature addition, which means the 100ºF+ degrees are also pushed even hotter. The increased temperatures throughout the day not only make the midday temperatures higher, but it also eliminates the relief humans need during the night to withstand the daytime temperatures. This would not be of much consequence if these heightened temperatures affected class or lab spaces that are normally vacant at night, but these magnified temperatures are being calculated in the Maseeh courtyard, a residential building. This could create health dangers for all students living in the residential hall, and even more so for those with pre-existing health conditions or those on medications.

It is also interesting to note that the M3 climate module recorded higher ground temperature than air temperature on June 25, but on July 06, it recorded higher air temperature than ground temperature. Although there is no definitive explanation for this switch in reported highs, there are several measured variables that could be of influence. For instance, the M3 climate module recorded high lux levels on June 25 to indicate prolonged time in strong ambient light, whereas on July 06, it measured very low lux levels on July 06 which indicated an overcast day. The M3 climate module also measures soil material in a larger planter that runs along the eastern side of the Maseeh courtyard. If watered, the moisture content in the soil could have affected the ground temperature, and with the continuous process of evapotranspiration, this changing humidity concentration from the ground to the air could also affect these measurements. The Maseeh courtyard is also surrounded on three sides by the building itself, with the remaining fourth side open to wind activity through a gate. The lack of wind activity in this area because of the surrounding building means that the heat is unable to dissipate and more likely congregates in the courtyard. This is also similar to the P1 climate module surroundings, as it is enclosed on two sides by Building 3 and does not experience much heat dispersal through wind activity. Coincidentally or not, the Maseeh climate modules and the P1 climate module all recorded the highest temperature readings over the three 24-hour time periods.

5.2 Study Limitations and Future Work

Although the climate modules were designed to consistently work over a 7-day period, there were a few extenuating circumstances that led to shortened data collection periods. A climate module in the Hive that was measuring the lawn was inexplicably exposed to the routine waterings via sprinklers. Despite the climate modules being resistant to water that falls from above, it is vulnerable to moisture from below. Ironically, the batteries used to power the climate modules were affected by high heat exposure due to being left exposed to the elements. The climate modules that measured especially high temperatures on campus also exhibited lowered battery life and thus, shortened measurement periods from 7 days to 3 or 4 days. The Arduino microcontroller also seemed to be affected by constant usage, as a few climate modules would no longer function simply with a refreshed supply of batteries but would also need a code reupload.

Without surveillance of any kind for the climate modules during measurement periods, they are all vulnerable to human interference, malicious or not. The ground temperature measurement especially could be tampered with by putting different material below the infrared temperature sensor. The climate modules that measured the more natural areas like planters and soil were also more exposed to wildlife like animals and insects, the latter of which were sometimes found within the modules but did not give tangible reason to believe that interference was had.

Distance among climate modules was not considered for this research. The climate module placement for each campus area was based on measuring the widest variety of ground material and surrounding architecture and landscape to capture a diverse campus temperature profile. As a result, there could be redundancies in the measured data because the climate modules were possibly placed too closely to each other.

Future work could take many forms from this research. This research measured six areas on campus, but there are other architectures, materials, and landscapes across campus that could provide additional temperature information for MIT. The climate modules could also be focused specifically on the vents that intake outdoor air for internal air conditioning. This would provide MIT with information that could help reduce energy and financial resources if external temperatures could be made lower with the help of heat dissipation techniques like green landscaping. The climate modules could also take a different form factor, much like the heat sensors that were mounted onto cars driven through Boston. Current future work in MIT's Senseable City Lab is developing bike-mountable temperature sensors that would allow users to record temperature on a more granular scale around campus to create more accurate heat maps of the area. Lastly, a process to more strongly correlate the campus materials and architecture to the surrounding air and ground temperature would also help inform the campus on what types of materials and landscapes to use in future projects to mitigate heat.

Chapter 6

Conclusion

With the ever-present threat of climate change, it becomes a greater urgency to measure our current surroundings in order to prepare for a warmer future. In order to create viable change globally, it is necessary to begin this change on a smaller, more local scale, as universal solutions tend to break down at more minute levels due to diverse conditions and exceptions. Not only do these efforts to create cooler living environments help slow climate change, it also helps contribute to human comfort and reduce energy and financial resources.

Climate modules were designed and created to record air temperature, ground temperature, relative humidity, light, and pressure across various areas on campus. The areas on campus measured included the Maseeh courtyard, the pedestrian walkway next to Building 31, the parking lot next to Building 3, the Hive, the MIT Medical courtyard area, and the courtyard outside the Welcome Center. Third party temperature stations off campus but within Cambridge and Boston were also used for the temperature data they collected. The Boston Logan Airport, the East Cambridge, the Port, and the Central Square Weather Underground stations reported similar environmental data as the campus climate modules.

The MIT campus area temperature measurements were compared to the Weather Underground station measurements. Although the Weather Underground stations report similar temperatures to each other, the campus climate module data reported higher temperatures overall, especially in the parking lot outside Building 3, the pedestrian walkway outside Building 31, and the Maseeh courtyard, though all campus areas generally reported higher temperatures than the Weather Underground stations. Additionally, the Boston Logan Airport Weather Underground station also reported some of the lowest temperatures.

The current method of reporting and forecasting weather and heat might be effective in a very general sense; however, the actual temperatures experienced may vary drastically depending on the surrounding materials, architecture, and landscape. Furthermore, the current process ASHRAE uses of determining building codes based on single climate data points at Logan airport for the Greater Boston area may not be truly representative of all areas, especially since the Boston Logan Airport Weather Underground station was among some of the lowest measured temperatures. Most importantly, the heightened temperatures measured in the Maseeh courtyard heralds possibly dangerous living conditions during the summer as the courtyard magnifies heat in the day and stays hot into the night, preventing residents from any nighttime relief from the increased daytime heat. Efforts must be continually made to reduce the larger effects of climate change, which is possible with future research.

Appendix A

Bill of Materials

Part	Manufacturer	Part Number	Units Purchased	Unit Price (USD)	Total (USD)
waterproof box - 8.6"×6.7"×4.3" opaque	Gratury	B08281V2RL	20	26.07	521.40
Arduino Nano 33 IoT	Arduino	ABX00027	20	19.00	380.00
Arduino MKR MEM Shield	Arduino	ASX00008	20	23.40	468.00
MLX90614 Infrared Temperature Sensor	Adafruit	1747	20	15.95	319.00
AHT20 Temperature and Humidity Sensor	Adafruit	4566	20	4.50	90.00
Adafruit VEML7700 Lux Sensor	Adafruit	4162	20	4.95	99.00

Part	Manufacturer	Part Number	Units Purchased	Unit Price (USD)	Total (USD)
Adafruit BMP280 Barometric Pressure Sensor	Adafruit	2651	20	9.95	199.00
CR1220 Battery - 10 pack	LiCB	B0797NRXZY	2	5.99	11.98
JST XH connectors	GeeBat	GB0011	10	11.99	119.90
Tripod	UBeesize	B09LQPTQB3	20	8.49	169.80
Battery case for AA - 6 pack	VQVAAQ	B07F43VWRQ	3	5.58	16.74
Batteries AA - 8 pack	Amazon	B00HZV9WTM	20	19.35	387.00
MicroSD Memory Cards - 10 pack	Gigastone	B07RVFZ3F3	2	44.98	89.96

Part	Manufacturer	Part Number	Units Purchased	Unit Price (USD)	Total (USD)
10uF capacitor	Digikey	493-11389-1-ND	25	0.25	6.25
PVC elbow connectors	McMaster Carr	4880K23	25	1.05	26.25
PETG tube - 1"OD 7/8"ID	McMaster Carr	9245K37	3	17.51	52.53

Appendix B

Arduino Code

```
/*

  SD card datalogger with 4 sensors


  Logging data from MLX, AHT20, VEML7700, and BMP280

  onto microSD card


  created  4 Nov 2021

  by Lauren Futami


*/


#include <SPI.h>

#include <SD.h>


#include <Adafruit_MLX90614.h>

#include <Adafruit_AHTX0.h>

#include "Adafruit_VEML7700.h"


#include <Wire.h>

#include <Adafruit_BMP280.h>
```

```
#include "RTClib.h"

const int chipSelect = 4;

Adafruit_MLX90614 mlx = Adafruit_MLX90614();
Adafruit_AHTX0 aht;
Adafruit_VEML7700 veml = Adafruit_VEML7700();
Adafruit_BMP280 bmp;
RTC_DS3231 rtc;

void setup() {
  // Open serial communications and wait for port to open:
  Serial.begin(9600);
  delay(3000); // to let sensors power up
//   while (!Serial) {
//    ; // wait for serial port to connect. Needed for native USB port only
//  }

  // SD CARD SETUP ---------------------------------------------------------
  Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don’t do anything more:
    while (1);
  }
  Serial.println("card initialized.");
  Serial.println("================================================");
```

```
// SD CARD END SETUP -----------------------------------------------------

// MLX SETUP -------------------------------------------------------------
Serial.println("Adafruit MLX90614 test");

if (!mlx.begin()) {
  Serial.println("Error connecting to MLX sensor. Check wiring.");
  while (1);
};

Serial.print("Emissivity = "); Serial.println(mlx.readEmissivity());
Serial.println("SENSOR 1 (MLX) ALL GOOD!");
Serial.println("================================================");
// MLX END SETUP ---------------------------------------------------------

// AHT20 SETUP -----------------------------------------------------------
if (! aht.begin()) {
  Serial.println("Could not find AHT? Check wiring");
  while (1) delay(10);
}
Serial.println("AHT10 or AHT20 found");
Serial.println("SENSOR 2 (AHT20) ALL GOOD!");
Serial.println("================================================");
// AHT20 END SETUP -------------------------------------------------------

// VEML7700 SETUP --------------------------------------------------------
if (!veml.begin()) {
  Serial.println("Sensor not found");
  while (1);
}
```

```
Serial.println("Sensor found");

veml.setGain(VEML7700_GAIN_1_8);
veml.setIntegrationTime(VEML7700_IT_25MS);

Serial.print(F("Gain: "));
switch (veml.getGain()) {
  case VEML7700_GAIN_1: Serial.println("1"); break;
  case VEML7700_GAIN_2: Serial.println("2"); break;
  case VEML7700_GAIN_1_4: Serial.println("1/4"); break;
  case VEML7700_GAIN_1_8: Serial.println("1/8"); break;
}

Serial.print(F("Integration Time (ms): "));
switch (veml.getIntegrationTime()) {
  case VEML7700_IT_25MS: Serial.println("25"); break;
  case VEML7700_IT_50MS: Serial.println("50"); break;
  case VEML7700_IT_100MS: Serial.println("100"); break;
  case VEML7700_IT_200MS: Serial.println("200"); break;
  case VEML7700_IT_400MS: Serial.println("400"); break;
  case VEML7700_IT_800MS: Serial.println("800"); break;
}

veml.setLowThreshold(10000);
veml.setHighThreshold(20000);
veml.interruptEnable(true);
Serial.println("SENSOR 3 (VEML7700) ALL GOOD!");
Serial.println("================================================");
// VEML7700 END SETUP ----------------------------------------------------
```

```
  // BMP280 SETUP ----------------------------------------------------------
  if (!bmp.begin()) {
    Serial.println(F("Could not find a valid BMP280 sensor, check wiring or "
                      "try a different address!"));
    while (1) delay(10);
  }

  /* Default settings from datasheet. */
  bmp.setSampling(Adafruit_BMP280::MODE_NORMAL,     /* Operating Mode. */
                  Adafruit_BMP280::SAMPLING_X2,     /* Temp. oversampling */
                  Adafruit_BMP280::SAMPLING_X16,    /* Pressure oversampling */
                  Adafruit_BMP280::FILTER_X16,      /* Filtering. */
                  Adafruit_BMP280::STANDBY_MS_500); /* Standby time. */
  Serial.println("SENSOR 4 (BMP280) ALL GOOD!");
  Serial.println("================================================");
  // BMP280 END SETUP ------------------------------------------------------

  // RTC SETUP ----------------------------------------------------------
  if (! rtc.begin()) {
    Serial.println("Couldn’t find RTC");
    Serial.flush();
    while (1) delay(10);
  }
  // RTC END SETUP ----------------------------------------------------------

  printDatastringInfo();
}

void loop() {
  Serial.println("Making data string...");
```

```
// make a string for assembling the data to log:
String dataString = "";

// populate dataString with 5 sensor readings
// groundTemp(F),airTemp(F),airHumidity(%),light(Lux),pressure(Pa)
String groundTemp = String(mlx.readObjectTempF());  //MLX

sensors_event_t AHThumidity, AHTtemp;
aht.getEvent(&AHThumidity, &AHTtemp);
String airTemp = String(AHTtemp.temperature*1.8+32);     //AHT20
String airHum = String(AHThumidity.relative_humidity);      //AHT20

String light = String(veml.readLux());       //VEML7700

String pressure = String(bmp.readPressure());    //BMP280

DateTime now = rtc.now();
String currentDate = "";
String currentTime = "";
String currentMonth = String(now.month());
String currentDay = String(now.day());
String currentYear = String(now.year());
String currentHour = String(now.hour());
String currentMinute = String(now.minute());
String currentSecond = String(now.second());
currentDate = currentMonth + "/" + currentDay + "/" + currentYear;
currentTime = currentHour + ":" + currentMinute + ":" + currentSecond;

dataString = currentDate + "," + currentTime + "," + groundTemp +
```

```
  "," + airTemp + "," + airHum + "," + light + "," + pressure;

  Serial.println("Writing data string...");

  // open the file. note that only one file can be open at a time,
  // so you have to close this one before opening another.
  File dataFile = SD.open("datalog.txt", FILE_WRITE);

  // if the file is available, write to it:
  if (dataFile) {
    digitalWrite(LED_BUILTIN, LOW); // LED Signal off if the SD is working
    dataFile.println(dataString);
    dataFile.close();
    // print to the serial port too:
    Serial.println("datastring: " + dataString);
  }
  // if the file isn’t open, pop up an error:
  else {
    Serial.println("error opening datalog.txt");
    digitalWrite(LED_BUILTIN, HIGH); // LED Signal on if the SD isn’t reading
  }

  Serial.println("Finished writing data string!");
  delay(180000);
}

void printDatastringInfo() {
  File dataFile = SD.open("datalog.txt", FILE_WRITE);

  // if the file is available, write to it:
```

```
 if (dataFile) {
   dataFile.println("Date,Time,groundTemp(F),airTemp(F),airHumidity(%),
   light(Lux),pressure(Pa)");
   dataFile.close();
 }
}
```

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