Comparing Near-Surface and Subsurface Conditions to Determine Impacts of Green Spaces in Urban/Suburban Areas

Undergraduate Research Thesis
Presented in partial fulfillment of the requirements for graduation with research distinction in Atmospheric Sciences in the undergraduate colleges of The Ohio State University
By
Tristan Bard

The Ohio State University
May 2025
Project Advisor: Professor Steven Quiring, Department of Geography
Thesis Committee: Professor Steven Quiring and Professor Alvaro Montenegro

Abstract

As urbanization continues to increase globally, so too does the expansion of impervious surfaces like asphalt. Urban areas are associated with buildings built close together, high population density, and large areas of impervious concrete and asphalt. These characteristics, along with many others, tend to increase near-surface and subsurface temperatures as compared with nearby rural environments. This is known as the urban heat island (UHI) effect. The UHI affects individuals living in cities by impacting their health, raising cooling costs, and increasing heat stress on infrastructure. The UHI is caused by changes in surface radiation flux due to anthropogenic surface materials. The purpose of this study is to investigate and compare the effects of asphalt and grass surfaces on radiation flux, near-surface temperature, and soil moisture to assess the importance of green space in urban settings. This study will identify the advantages of urban vegetation. Specifically, these data were measured over a two-week period during October, in Dublin, Ohio which is just outside of Columbus. This study quantified how different land covers influenced the local microclimate and UHI. This study found that asphalt was on average 0.37°C warmer than grass, with a maximum daytime difference of +1.41°C and nighttime difference of -1.48°C. Grass lost more soil moisture daily (0.0215%) compared to asphalt (0.0085%), and absorbed significantly more moisture during rainfall, peaking at 0.214 m^3/m^3 versus asphalt's 0.17 m^3/m^3. Although radiation data were likely flawed, asphalt showed higher outgoing shortwave radiation than grass, contrary to expected albedo-based behavior. Despite these differences, temperature and soil moisture data between surfaces showed strong correlations but statistical differences.

These findings provide valuable information for urban planning and climate adaptation strategies for the future development of cities.

Dedication

To the brains of the future. Believe you can achieve anything and nothing will stop you.

Acknowledgements

A special thank you to my aunt and uncle for allowing me to set up this project in their driveway and to my cousins for their willingness to dig holes in their yard. Thank you to The Ohio State University for providing the resources used to conduct this project, to Dr. Quiring for advising me through this process, Dr. Montenegro for joining my committee, and to my unofficial co-advisor Jackie Beck for helping me complete this work and believing in me.

Table of Contents

List of Figures

Chapter 1. Introduction

1.1 Urban Heat Island

Cities are often much warmer than the surrounding rural areas. This is known as the urban heat island (UHI) effect. The American Meteorological Society (AMS) defines the UHI as a closed isotherm indicating surface warmth associated with human disturbances (American Meteorological Society, 2024). This is a well-researched phenomenon where temperatures in urban areas can reach as high as 10°C above nearby woodlands (Kim 1992). This disparity in temperature has broad implications, affecting energy consumption, human health, and ecological systems within and beyond city limits.

There are four primary types of UHI: surface, subsurface, canopy layer, and boundary layer (Voogt et al., 2017). This project focuses on quantifying the surface and subsurface UHI. The surface heat island effect is the temperature difference of the near-surface atmosphere as it reacts with urban materials and infrastructure, while the subsurface focuses on the impact these human materials have on the soil (Voogt et al., 2017). Many of these materials can impact the permeability of surfaces. Impervious surfaces, such as metal or asphalt prevent water from infiltrating. While natural surfaces, such as grass or soil will allow for greater infiltration. This difference in permeability directly influences the surface energy balance. Impervious surfaces reduce infiltration and evapotranspiration, limiting latent heat flux and increasing sensible heat flux, which intensifies surface and near-surface warming. In contrast, permeable surfaces enhance soil moisture availability, enabling more evaporative cooling, thus reducing daytime temperatures and mitigating the UHI (Voogt et al. 2017).

1.2 Radiation Balance

Heating and cooling on Earth is a result of radiation balances (Hartmann et al. 1986). This balance is composed of incoming radiation from the sun as well as the radiation reflected by the surface. A surface's ability to reflect radiation is known as its albedo. Albedo is defined as:

$$\alpha = \frac{K\uparrow}{K\downarrow}$$

where α is albedo, $K\uparrow$ is reflected shortwave radiation and $K\downarrow$ is incoming shortwave radiation (Voogt et al. 2017). Cities often have a low albedo (0.1 to 0.2) due to the materials that comprise them, especially when compared to the albedo measurements of grassy areas (0.2 to 0.3) (Smith et al. 2023). Materials commonly found in cities like asphalt, concrete, and brick absorb and retain heat more effectively than natural surfaces, contributing to increased ambient temperatures.

The total available energy at the surface is described by the net radiation equation:

$$Rn = (K\downarrow + L\downarrow) - (K\uparrow + L\uparrow)$$

where $K\downarrow$ and $K\uparrow$ are the incoming and reflected shortwave radiation, and $L\downarrow$ and $L\uparrow$ are the incoming and outgoing longwave radiation (Voogt et al. 2017). Urban surfaces typically reflect less shortwave radiation and emit less longwave radiation due to lower emissivity, thereby increasing Rn.

The surface energy balance (SEB) describes how this net radiation is broken up:

$$Rn = H + LE + G + \Delta S$$

Here, H is sensible heat flux, LE is latent heat flux, G is ground heat flux, and ΔS is the change in heat storage within the system (Voogt et al. 2017). In vegetated environments, a significant portion of Rn supports latent heat flux (evapotranspiration), which cools the surface and moderates near-surface air temperatures.

In contrast, urban environments alter this energy distribution. Impervious surfaces and limited vegetation suppress latent heat flux (LE), while increasing both sensible heat (H) and ground heat flux (G). Asphalt and concrete, with high thermal conductivity and heat capacity, store substantial heat during the day and release it slowly overnight, maintaining elevated nighttime temperatures (Voogt et al. 2017). This thermal storage and redistribution are major contributors to the UHI effect.

Overall, the reduction in LE and increase in H, G, and ΔS create an energy imbalance in urban settings. These altered fluxes enhance diurnal temperature ranges and increase thermal stress, particularly during heat waves (Voogt et al. 2017). Collectively, these changes underscore how urban surface choices fundamentally reshape the local energy budget, emphasizing the need for green infrastructure in climate-resilient urban design.

1.3 Street Canyons

Downtown areas often consist of tall buildings that create "street canyons" (Arnfield 1982). These street canyons influence airflow and can reflect and trap radiation, further amplifying temperatures within cities. The geometry of these canyons results in multiple reflections of solar radiation, reducing the potential for heat to escape and prolonging the retention of thermal energy. At the base of almost every street canyon, there is asphalt, the most common paving material in the United States (Holley 2003). It has a low albedo which contributes to urban heating. The heat-retaining properties of asphalt are particularly pronounced in regions with high levels of solar radiation, were roadways and parking lots act as persistent heat sources even after sunset. Urban surfaces like asphalt and concrete are not only effective at absorbing solar radiation due to their low albedo, but they also play a significant role in ground heat flux and thermal storage. These materials have a high heat capacity and thermal conductivity, enabling them to absorb substantial amounts of energy during the day and release it gradually during the night. This delayed release of stored heat contributes to elevated nighttime temperatures, prolonging thermal stress in urban environments and reinforcing the UHI effect (Voogt et al. 2017).

There are many types of asphalt, and each can impact heat flux in different ways (Mohajerani et al., 2017). There are many types of asphalt, and each can impact heat flux in different ways (Mohajerani et al., 2017). Lighter-colored asphalts or those treated with reflective coatings can significantly reduce surface temperatures by increasing surface albedo and reflecting a larger fraction of incoming solar radiation (Mohajerani et al.

2017). These so-called "cool pavements" are increasingly used in urban design to mitigate surface heating. In contrast, traditional black asphalt has a much lower albedo and absorbs a greater proportion of solar energy, contributing more strongly to surface heat storage and re-radiation (Voogt et al. 2017). Furthermore, porous types of asphalt may also influence thermal behavior by promoting limited water infiltration, which can lead to slight increases in evaporative cooling (Mohajerani et al. 2017).

1.4 Surface Thermal Properties

Grass and asphalt have distinct thermal properties that influence surface and near-surface temperatures. Asphalt has a high emissivity of ~0.96 compared to short grass which has an emissivity of ~0.90 (Voogt et al., 2017). Emissivity is a ratio of radiation emitted from a surface to the emission of a black body at the same temperature (American Meteorological Society 2024). This means that while asphalt will absorb heat faster, due to the lower albedo, grass will store the heat for longer due to its lower emissivity (Madjidi et al., 2013). Studies show that grass-covered areas remain significantly cooler than asphalt surfaces, particularly during the day, due to their ability to dissipate heat more effectively (Madjidi et al., 2013). Unlike asphalt, grass-covered surfaces actively release latent heat through evapotranspiration. This process transfers energy from the surface to the atmosphere in the form of water vapor, providing a natural cooling effect that reduces surface and near-surface air temperatures.

1.5 Limitations of Previous Studies

While urban centers are the primary contributors to the UHI effect, suburban areas are also susceptible to localized heating due to widespread asphalt use in roads, driveways, and parking lots (Sima et al. 2024). While this research is undoubtedly significant and informative, certain gaps remain that warrant further investigation. To start, most of the research is conducted in similar ways. Either data are collected at two different locations comparing cities to surrounding areas with different surface classifications (Kim 1992), or they are gathered at two distinct points within city limits (Smith et al. 2023). The latter method measures the microclimate of grass and asphalt surfaces within the same general region, but not in identical locations. This makes a direct comparison challenging. The influence of microclimates, variations in shading, and differences in land use further complicate these analyses. To date, there has been less focus on suburbs despite their rapid expansion and increasing contribution to heat retention. While urban areas contribute most to the UHI, they are often the hardest to modify due to infrastructure constraints and economic considerations. In contrast, suburban areas have higher flexibility in their surface choices, providing a unique opportunity to implement mitigation strategies such as increased green spaces, reflective pavements like concrete, and using alternative materials that balance urban functionality with environmental sustainability. This thesis will assess the impacts of replacing asphalt surfaces with grass on the microclimate. This analysis can help inform planning and mitigation strategies aimed at reducing heat accumulation urban and suburban areas.

Chapter 2. Data & Methods

2.1 General Information

This thesis recorded hourly maximum, minimum, and average of air temperature, solar radiation, and soil moisture in Dublin, Ohio from October 7th at 4:00pm till October 21st at 7:00pm. The location of this project consisted of a driveway and grass yard that connected as shown in Figure 1. This driveway, located in the suburb of Dublin, Ohio, was specifically selected because the grass and asphalt surface where measurements were taken were in close proximity. Therefore, they experienced identical atmospheric conditions. In addition, the two sites were not influenced by shading from buildings or trees to disrupt solar radiation measurements. Once data were collected, Python was used for analysis and statistical testing. Time series were composed for each of the variables showing the changes in data over time. Although maximum, minimum, and mean temperatures were recorded during this experiment, only the results for mean temperature are discussed in this thesis. This is because the maximum, and minimum results are quantitatively similar.

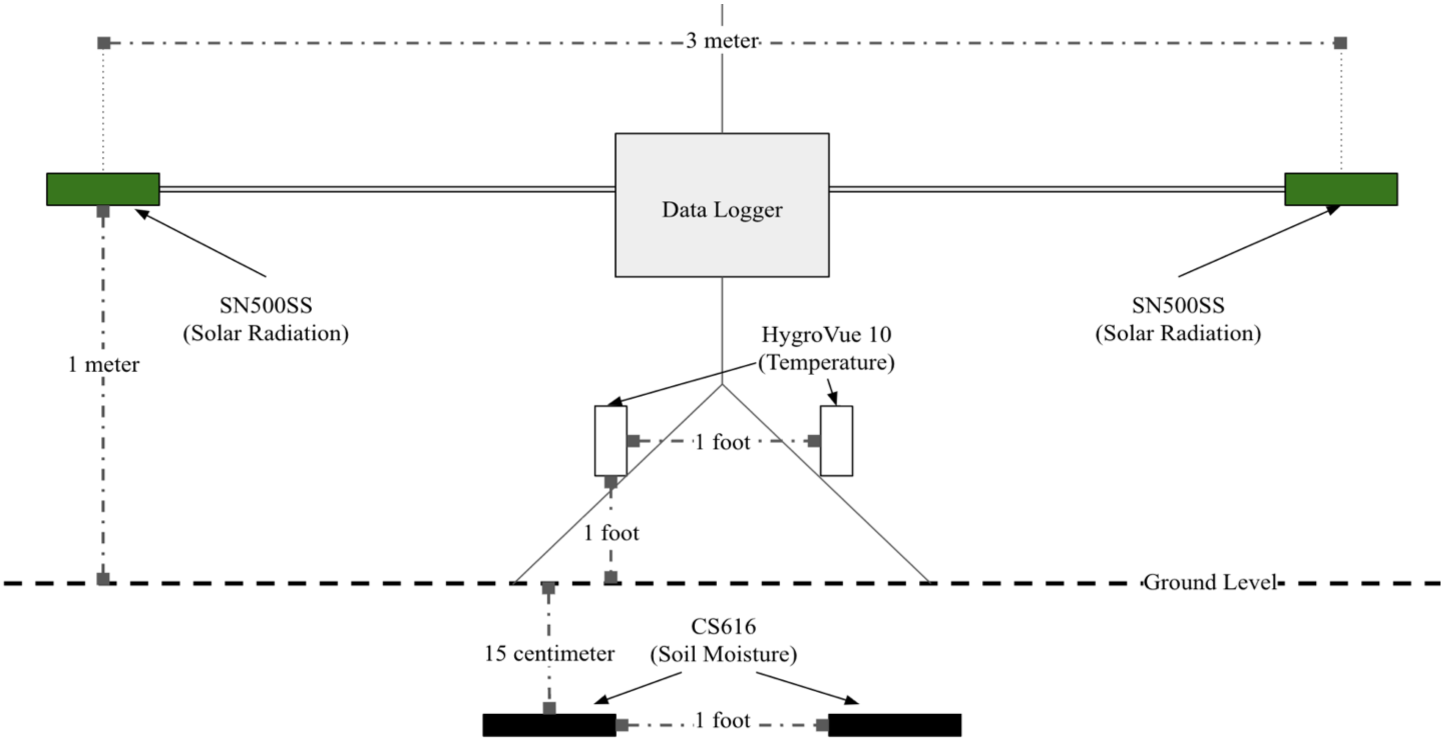

Figure 2: Schematic showing sensors that were used along with the distances from the ground as well as one another.

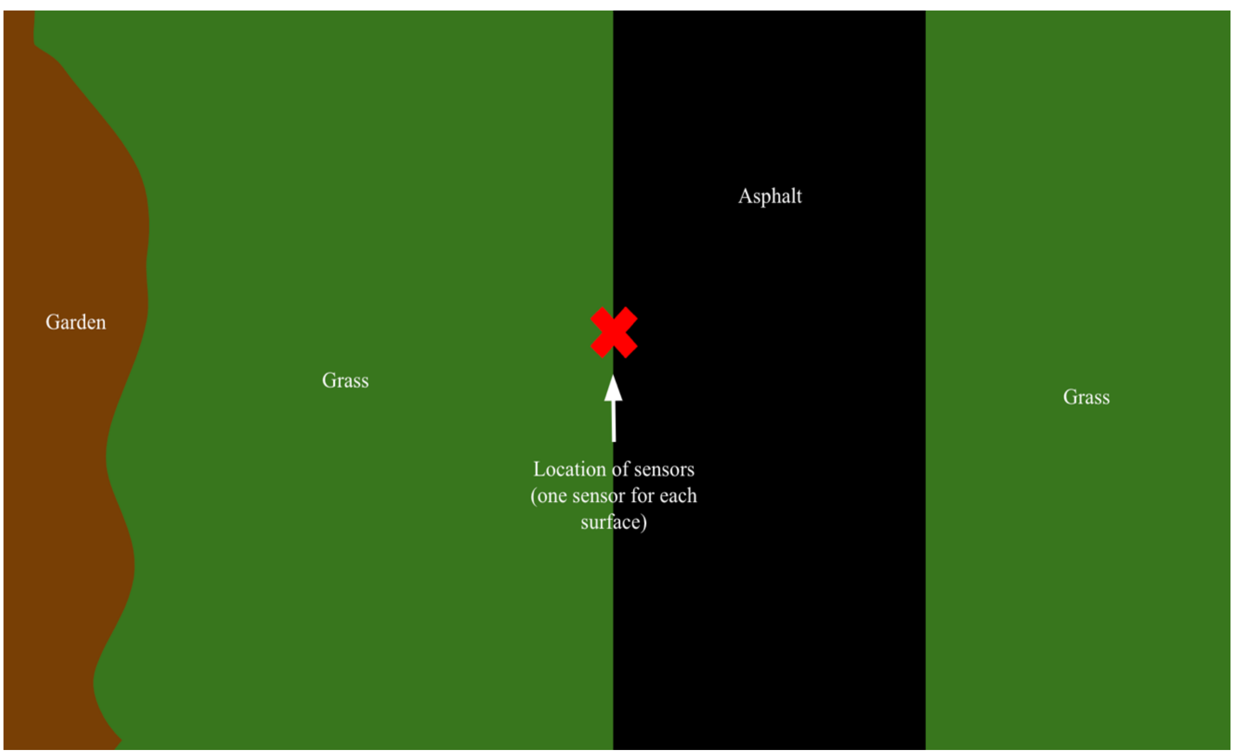

Figure 1: Site map showing area recording devices were set up. Grass and asphalt were closely bonded together along the edge of the driveway with a small garden well outside of the recording area.

2.2 Temperature

A HygroVue 10 was used to measure air temperature. The sensors were installed 0.33 m above the surface. This was done to collect the air temperature closely related to the surface UHI while minimizing any interference from mixing with air not impacted by the surface UHI. According to Campbell Scientific, the HygroVue 10 has an error of ±0.2°C (over the range -40°C to +70°C) and ±0.1°C (over the range 20°C to 60°C)).

2.3 Net Radiation

An Apogee SN500SS net radiometer was used to measure incoming and outgoing long and shortwave radiation. The SN500SS provides separate measurements of incoming radiation (L↓, K ↓) and outgoing radiation (L ↑, K ↑). These sensors were installed 1 m above the ground surface to measure radiation around the center of human height. The error of the SN500SS is reported by Apogee at ±5%.

2.4 Soil Moisture

A Campbell Scientific CS616 was used to measure volumetric water content (VWC) of the soil. Two CS616s were 15 cm below the surface, one under the grass and one under the asphalt. These measurements are used for characterizing the soil saturation due to infiltration of precipitation. Campbell Scientific reports an error of ±2.5% VWC (using standard calibration with bulk EC of ≤ 0.5 dS m^{-1}, bulk density of ≤ 1.55 g cm^{-3}, and measurement range of 0% to 50% VWC).

Chapter 3. Results and Discussion

3.1 Temperature

Temperature readings over the 14-day period, displayed in Figure 3, showed that temperature during the peak heating of the day was always significantly warmer over asphalt. This is true even when there was significant cloud cover and rain, such as between hours 150 and 225. This is a result of the difference in thermal properties between grass and asphalt. Grass is better at retaining its temperature when compared with asphalt but does not heat up nearly as much as asphalt during the afternoon hours (Madjidi et al. 2013). It also is a function of the latent and sensible heat fluxes. Greater evaporative cooling over the grass surface than the asphalt. Figure 4 visualizes the difference between the two recordings in Figure 3 further displaying the disparity in the respective thermal properties. During the day the maximum difference showed that asphalt was 1.41°C warmer than the grass but at night the grass was 1.48°C warmer.

On average, the asphalt was about 0.37°C warmer than the grass. More specifically, the average temperature was 10.91°C for asphalt and 10.67°C for grass with a difference of +0.24°C to asphalt. The maximum temperature over asphalt was 25.64°C and for grass was 25.14°C (both at hour 122) with a difference of +0.50°C to asphalt. The minimum temperatures recorded were -1.33°C for asphalt and -1.64°C for grass (both at hour 233) with a difference of +0.31°C to asphalt. While the surface maximums, minimums, and averages for this thesis will be unique, the differences between the surfaces can be compared to Madjidi et al. (2013) found similar results with a maximum temperature difference reported at +1.40°C to asphalt and the difference between the minimums was found to be 0.80°C. This shows that each surface reacted similarly to atmospheric temperature changes however, their impact on near surface temperature were different. Asphalt is significantly warmer than grass during the peak heating in the afternoon hours. However, grass maintained a more consistent temperature during the evening.

The grass and asphalt had a correlation of 0.996 with a p-value of 2.225e-308. This indicates that both locations responded consistently to atmospheric changes in a similar way, even though the absolute near-surface atmospheric temperatures were different.

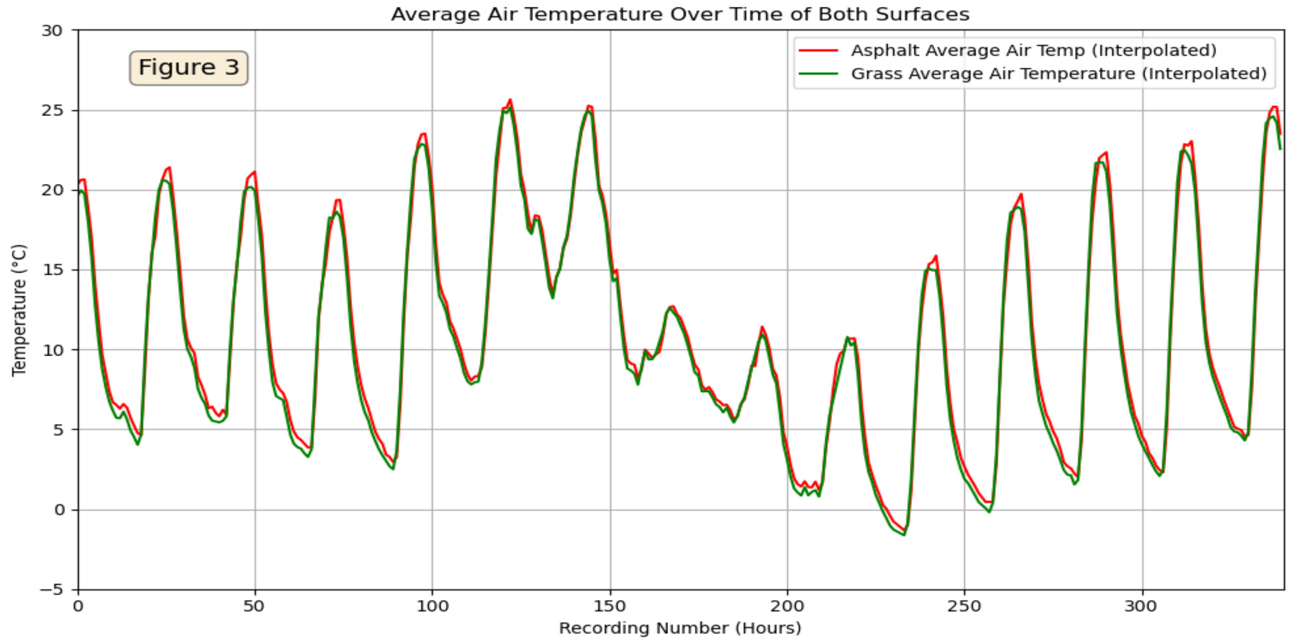

Figure 3: Shows average air temperature over time measured above asphalt and grass surfaces. Data are interpolated to show the diurnal temperature cycle across the entire study period. Asphalt air temperatures (red line) consistently trend slightly warmer than grass air temperatures (green line), especially during peak daylight hours. Record 0 represents 10/07/2024 at 06:00 EST and the final record represents 10/21/24 at 19:00 EST.

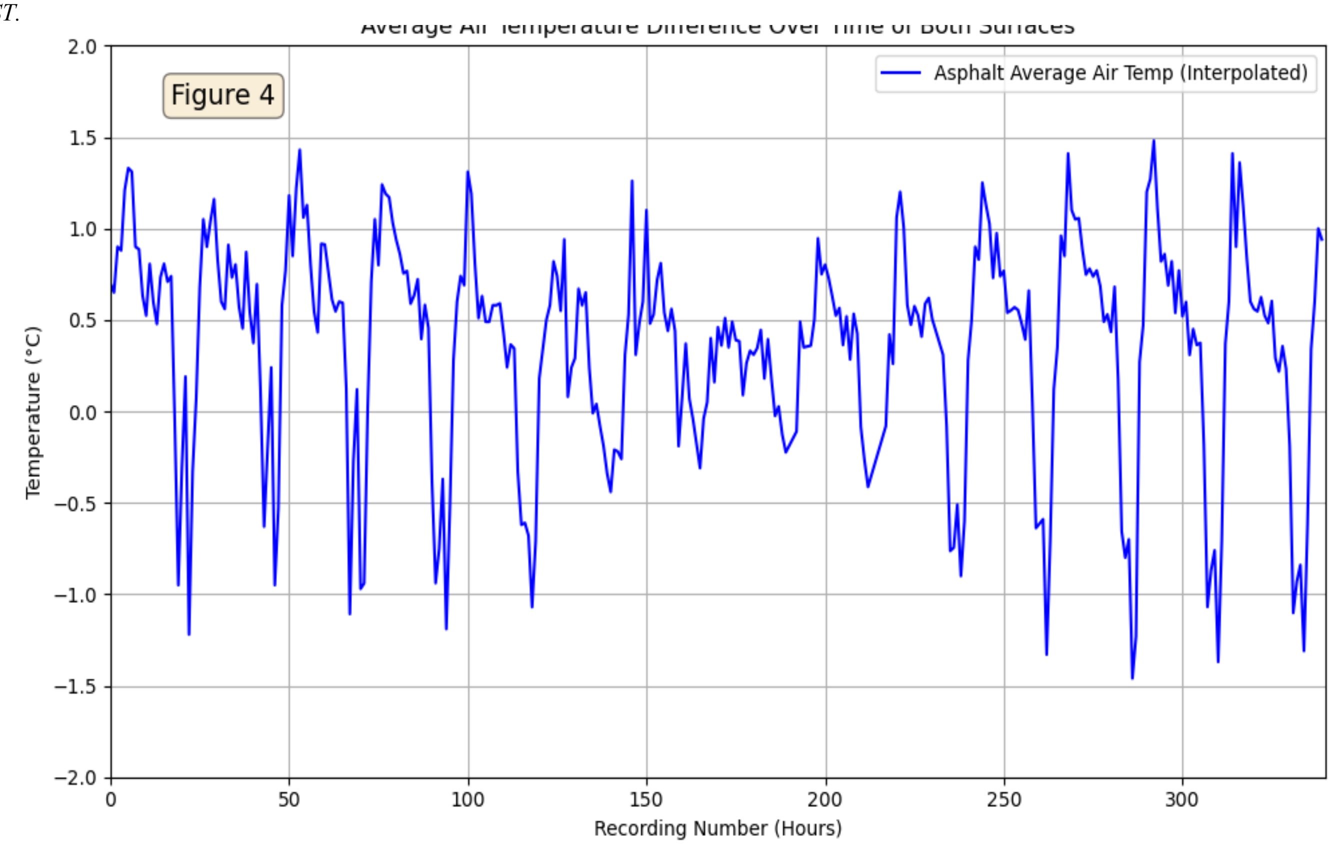

Figure 4: Difference between average air temperature over time measured above asphalt and grass surfaces. Shows the difference of asphalt minus grass average temperature. Record 0 represents 10/07/2024 at 06:00 EST and the final record represents 10/21/24 at 19:00 EST.

3.2 Soil Moisture

When analyzing the collected soil moisture data, there is a clear diurnal variation in soil moisture (Verhoef et al. 2006). As seen in Figure 5, as the air began to warm soil moisture increased, as it cooled moisture decreased. There are two major differences between the asphalt surface and the grass surface. First, the soil beneath the grass lost more soil moisture than the soil beneath the asphalt when excluding the rainfall event. Each day grass averaged a loss of about 0.0215% moisture while asphalt averaged a loss of only about 0.0085%. While this loss is similar and rather small, it is likely that grass loss is slightly more due to evapotranspiration while the asphalt acted as a cap keeping some moisture in. Similar processes can be seen in the Verhoef et al. (2006) for grass as well as Riise work for pavement. During the period of rain around hour 180, grass gained more moisture than asphalt. This was due to the impervious nature of the asphalt surface. As a result, most water was lost through runoff. Grass soil moisture reached a maximum value at hour 185 peaking at 0.214 m^3 m^{-3}, while asphalt peaked at 0.17 m^3 m^{-3} at hour 193. This further shows the effect of surface penetrability on soil moisture. It took eight additional hours for moisture to peak beneath the asphalt which is be attributed more to moisture from the grass surface being transported laterally through the soil beneath the pavement. The correlation for these two measurements is 0.911 with a p-value of 1.126e-131. This indicates a strong correlation between the two sets of soil moisture measurements. However, a paired t-test score of -3.1333 showed that there is a statistically significant difference between the mean VWC in the grass and asphalt locations.

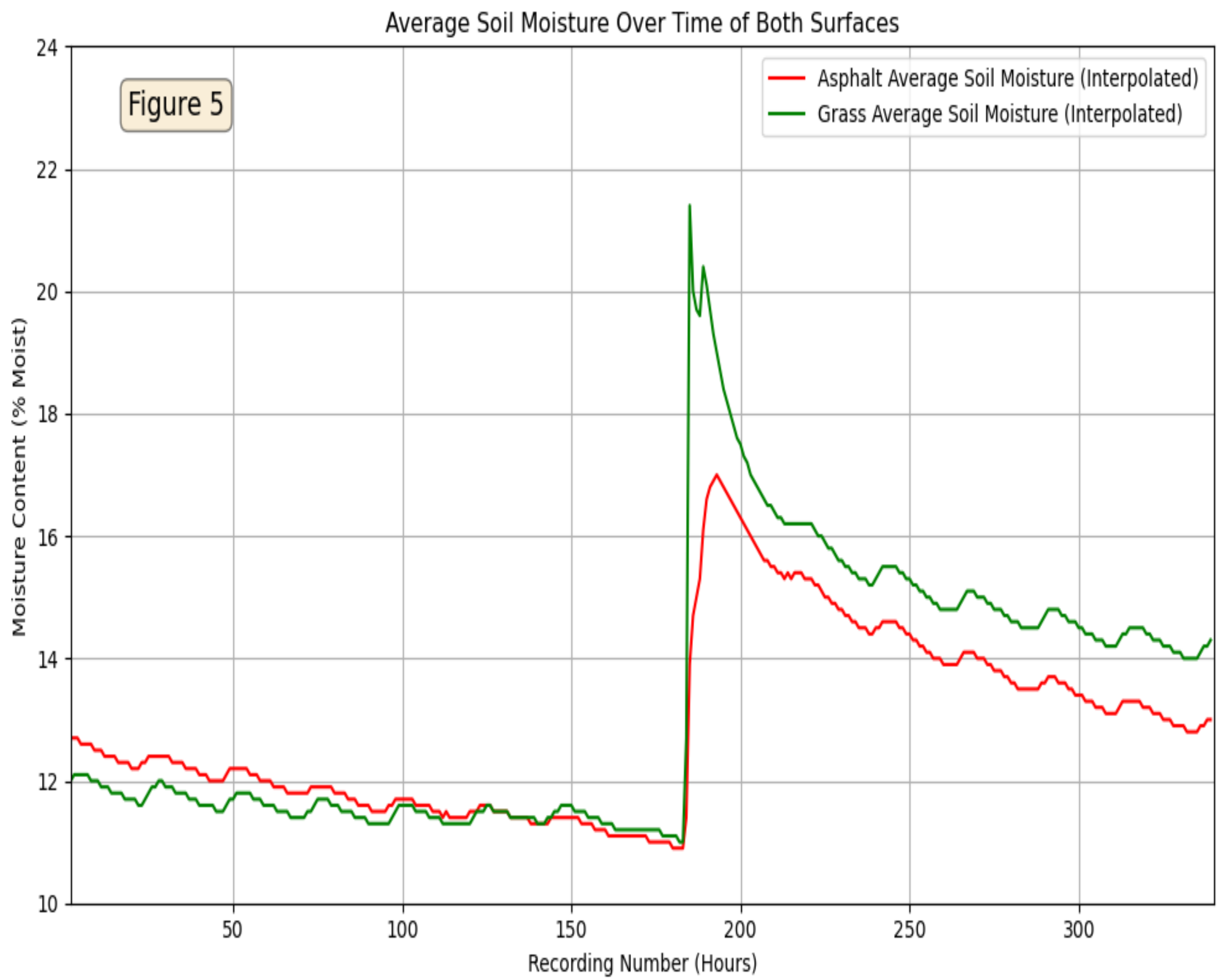

Figure 5: Average soil moisture content over time beneath asphalt and grass surfaces. A rainfall event is clearly visible around hour 185, after which grass (green line) retains substantially more moisture than asphalt (red line). Grass surfaces show higher and more sustained moisture levels following precipitation. Record 0 represents 10/07/2024 at 06:00 EST and the final record represents 10/21/24 at 19:00 EST. Rainfall occurred between record 186 (10/15/2024 at 08:00 EST) and record 210 (10/16/2024 at 08:00 EST)

3.3 Net Radiation

While much of the other data within this project was logically sound, the radiation recordings did not seem to. First, the incoming radiation data for each surface (Figures 6.a. and 6.b. respectively) should be identical. This is because the sensors were set only about three meters apart. With such a short difference between the two sensors the incoming radiation would be the same. Additionally, their positioning was carefully selected to prevent interference from shadows and even if there was a misjudgment, it would only affect a moment each day at the same time, not the entire dataset. A Runs test and Durbin-Watson test was run on each of the datasets, and it was found that the error was likely random. The average percent error of the data is much greater than the listed present error of ±5% (average error of the recorded data were calculated to be ~25%). After speaking with an Apogee representative, it is hypothesized that water vapor infiltrated the lens cover during shipping of the sensor leading to inconsistencies in measurement data. However, in this thesis, this data is going to be assumed as true.

The average shortwave incoming radiation (K↓) was 111.51 W/m² for grass and 98.05 W/m² for asphalt. The maximum K↓ values were 693.1 (hour 24) for grass and 745.3 (hour 23) for asphalt. Minimum K↓ was -1.173 (hour 6) for grass and -0.982 (hour 14) for asphalt. The outgoing shortwave radiation (K↑) showed averages of 9.24 W/m² for grass and 17.76 W/m² for asphalt. Maximum K↑ values were 65.13 (hour 71) for grass and 156.0 (hour 23) for asphalt. The average longwave incoming radiation (L↓) was 311.81 W/m² for grass and 308.25 W/m² for asphalt. The maximum L↓ values were 400.4 (hour 120) for grass and 393.3 (hour 120) for asphalt. Minimum L↓ was 256.8 (hour 204) for grass and 254.5 (hour 201) for asphalt. The average longwave outgoing radiation (L↑) was 388.49 W/m^2 for grass and 371.26 W/m^2 for asphalt. The maximum L↑values were 490.6 (hour 0) for grass and 488.9 (hour 95) for asphalt. Minimum L↑ was 325.6 (hour 233) for grass and 310.7 (hour 233) for asphalt. As prefaced in the previous paragraph, each of these values should be nearly identical over each surface.

If these data are considered accurate, the asphalt surface reflects more radiation than it absorbs, thus recording more outgoing shortwave radiation than that of the grass, but less outgoing longwave respectively. The reflectance (shortwave) was highest during the afternoon for both surfaces; however, the peak for the asphalt was much higher. This relation does not reflect what is expected based upon the assumed albedo values of both surfaces. According to asphalt data recorded by Sen and Roesler (2016) and grass data recorded by Wang and Davidson (2007), grass typically has an albedo that is nearly two times the albedo of asphalt. With knowledge of this data the expectation would be that grass would have greater outgoing shortwave values and smaller outgoing longwave values. Each form of radiation showed significant Pearson correlation when compared with the same radiation over each surface with values ranging from 0.917 to 0.977 with p-values ranging from 1.205e-132 to 2.396e-222.

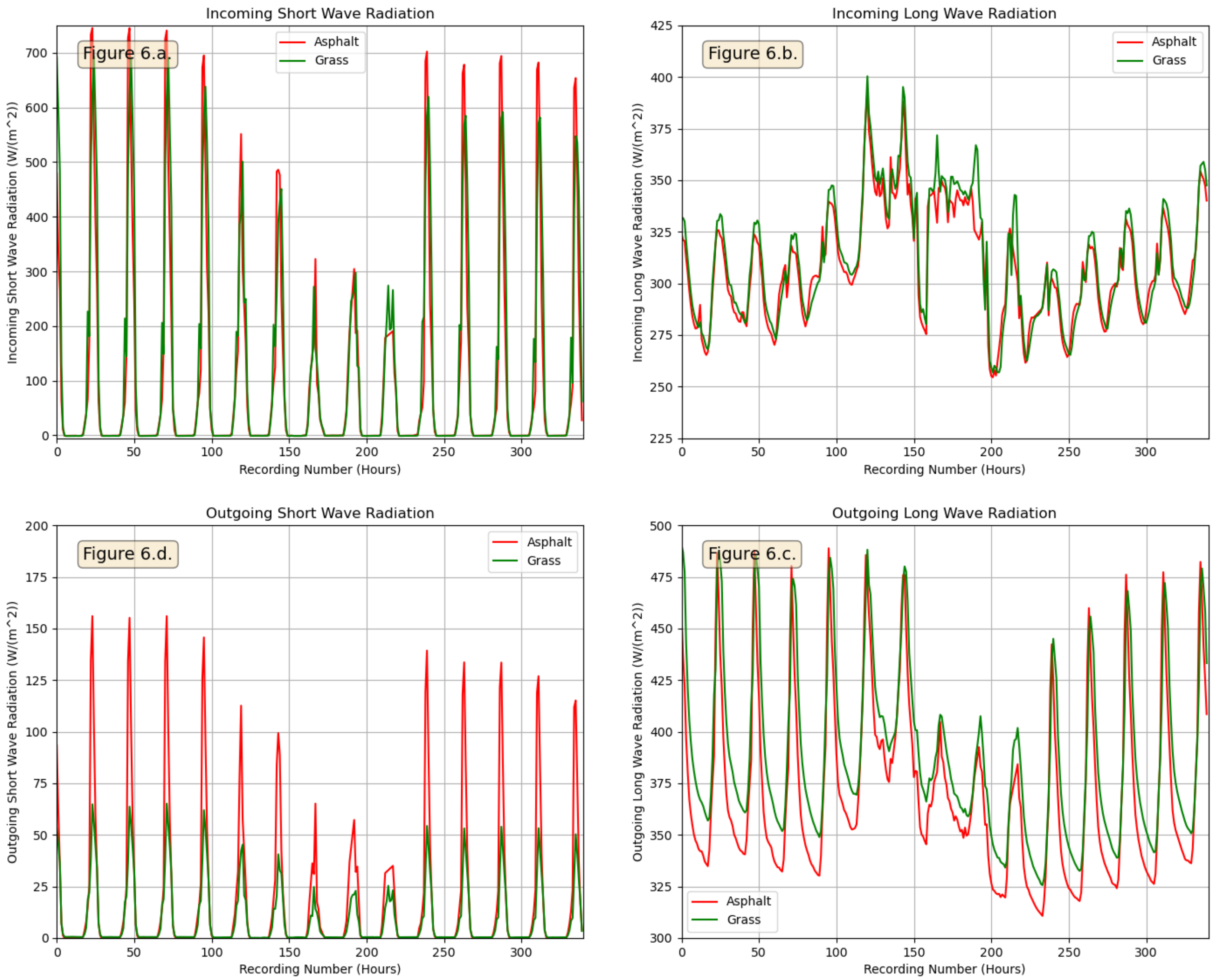

Figure 6: Figure 6.a. Incoming Shortwave Radiation: Both surfaces receive nearly identical incoming solar radiation, peaking during midday hours. Minor deviations reflect possible shading or cloud variability. Figure 6.b. Incoming Longwave Radiation: Incoming longwave radiation is slightly higher over grass than asphalt, particularly during nighttime hours, possibly due to enhanced atmospheric moisture and thermal emission. Figure 6.c. Outgoing Longwave Radiation: Outgoing longwave radiation is generally higher over grass, reflecting greater thermal emission from the cooler, moister surface. Asphalt exhibits lower nighttime emissions due to slower cooling. Figure 6.d. Outgoing Shortwave Radiation: Asphalt reflects significantly more shortwave radiation than grass, consistent with its higher albedo. Grass absorbs more incoming radiation, contributing to differences in surface energy balance. Record 0 represents 10/07/2024 at 06:00 EST and the final record represents 10/21/24 at 19:00 EST.

4. Conclusion

4.1 Synopsis

Understanding the differences in near surface/subsurface data as it pertains to grass and asphalt surfaces is critical to advancing the knowledge of urban microclimatology. This research addresses the scientific need to quantify how surface materials influence variables that directly impact human day-to-day life. By providing detailed measurements and analysis, this study fills the gaps when directly researching grass and asphalt in the exact same location to show the potential impact of replacing asphalt with grass in that area. Insights like these are important when attempting to mitigate and optimize sustainable urban design.

The results of this research revealed that asphalt consistently produced higher near-surface air temperatures than grass, particularly during afternoon peak heating hours, averaging 0.37°C warmer. Additionally, grass was able to gain more soil moisture during rainfall, indicating its superior ability to moderate moisture and temperature fluxes. Although solar radiation data presented anomalies likely due to instrumentation error, a general trend showed that asphalt reflected more shortwave radiation and emitted less longwave radiation, suggesting a distinct surface energy balance. These findings confirm that surface material choice meaningfully alters local microclimates.

With analysis of this data along with further studies of the same nature, the environmental benefits of grassy surfaces in urban/suburban areas can be seen. This data will help provide further information to city planners as they improve and develop their areas. Additionally, homeowners can use this data to make decisions about what to do on their own property. While there are many benefits to both surfaces, grass surfaces will help improve cooling in cities which will benefit all citizens. The hope is that data like this can influence the replacement of unneeded asphalt surfaces such as abandoned lots with green spaces.

4.2 Future Studies

There are several important questions that emerged during the course of this thesis. For instance, if multiple rainfall events had been recorded, would the soil moisture data for grass show an exponential growth pattern due to cumulative water absorption? Additionally, had the net radiometers functioned as intended, would the recorded solar radiation data have aligned with findings from previous studies, thereby strengthening the reliability of our measurements? It is also worth considering how these data might vary in a different setting, whether due to changes in geographic location, urban density, or microclimatic conditions.

Looking ahead, there are several steps that could enhance the robustness of this research. Future trials should be conducted in a similar environment, but with properly calibrated net radiometers to ensure accuracy. Extending the study over a longer time frame and across different seasons would offer a more comprehensive understanding of temporal variability. Moreover, incorporating a broader range of surface types—such as various grasses and asphalt of different ages—would allow for a deeper comparison of how different materials interact with solar radiation and retain moisture.

References

Aboufoul, M., N. Shokri, E. Saleh, C. Tuck, and A. Garcia, 2019: Dynamics of water evaporation from porous asphalt. *Construction and Building Materials*, **202**, 406–414, https://doi.org/10.1016/j.conbuildmat.2019.01.043.

American Meteorological Society, 2024: *Glossary of Meteorology*. 2nd ed. https://glossary.ametsoc.org, accessed 26 Mar 2025.

Arnfield, A. J., 1982: An Approach to the Estimation of the Surface Radiative Properties and Radiation Budgets of Cities. *Physical Geography*, **3**, 97–122, https://doi.org/10.1080/02723646.1982.10642221.

Benrazavi, R. S., K. Binti Dola, N. Ujang, and N. Sadat Benrazavi, 2016: Effect of pavement materials on surface temperatures in tropical environment. *Sustainable Cities and Society*, **22**, 94–103, https://doi.org/10.1016/j.scs.2016.01.011.

Coakley, J. A., 2003: REFLECTANCE AND ALBEDO, SURFACE. *Encyclopedia of Atmospheric Sciences*, Elsevier, 1914–1923.

Hartmann, D. L., V. Ramanathan, A. Berroir, and G. E. Hunt, 1986: Earth Radiation Budget data and climate research. *Reviews of Geophysics*, **24**, 439–468, https://doi.org/10.1029/RG024i002p00439.

Holley, I. B. (Irving B., 2003: Blacktop: How Asphalt Paving Came to the Urban United States. *Technology and Culture*, **44**, 703–733.

KIM, H. H., 1992: Urban heat island. *International Journal of Remote Sensing*, **13**, 2319–2336, https://doi.org/10.1080/01431169208904271.

Madjidi, F., A. A. Bidokhti, S. Ghader, and N. Mansori, 2013: Cooling and Warming Effects of a Grass Covered Area and Adjacent Asphalt Area in a Hot Day. *International Journal of Occupational Hygiene*, **5**, 56–63.

Mohajerani, A., J. Bakaric, and T. Jeffrey-Bailey, 2017: The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, **197**, 522–538, https://doi.org/10.1016/j.jenvman.2017.03.095.

Riise, T., 1952: *Soil moisture under the concrete pavement of an airport*. 7 pp.

Sen, S., and J. Roesler, 2016: Aging albedo model for asphalt pavement surfaces. *Journal of Cleaner Production*, **117**, 169–175, https://doi.org/10.1016/j.jclepro.2016.01.019.

Sima, L., Y. Liu, J. Zhang, and X. Shang, 2024: Research on Summer Hourly Climate-Influencing Factors in Suburban Areas of Cities in CFA Zone—Taking Chengdu, China as an Example. *Urban Sustainability: Sustainable Housing and Communities*.

Smith, I. A., M. P. Fabian, and L. R. Hutyra, 2023: Urban green space and albedo impacts on surface temperature across seven United States cities. *Science of The Total Environment*, **857**, 159663, https://doi.org/10.1016/j.scitotenv.2022.159663.

Verhoef, A., J. Fernández-Gálvez, A. Diaz-Espejo, B. E. Main, and M. El-Bishti, 2006: The diurnal course of soil moisture as measured by various dielectric sensors: Effects of soil temperature and the implications for evaporation estimates. *Journal of Hydrology*, **321**, 147–162, https://doi.org/10.1016/j.jhydrol.2005.07.039.

Voogt, J. A., G. Mills, and J. A. /Oke Voogt T. R., 2017: *Urban Climates*.

Wang, S., and A. Davidson, 2007: Impact of climate variations on surface albedo of a temperate grassland. *Agricultural and Forest Meteorology*, **142**, 133–142, https://doi.org/10.1016/j.agrformet.2006.03.027.