From ACE to ACS: Refining Urban Albedo-Temperature Metrics by Integrating Surface Energy Flux Responses

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Introduction

- Albedo (α) values represent how much light is reflected off a surface
- Albedo Cooling Effectiveness (ACE) gives cooling of temperatures (ΔT) per albedo

$$ACE = \frac{-\Delta T}{\Delta\alpha} \times \frac{total\ area}{building\ area}$$

- Albedo Cooling Sensitivity (ACS), accounts for variations of surface types for ACE

$$ACS = \frac{ACE}{SW_{in}} = \frac{-\Delta T}{\Delta\alpha \times SW_{in}} \times \frac{total\ area}{building\ area}$$

- Goal: Investigate effects of albedo and surface type on near surface temperatures

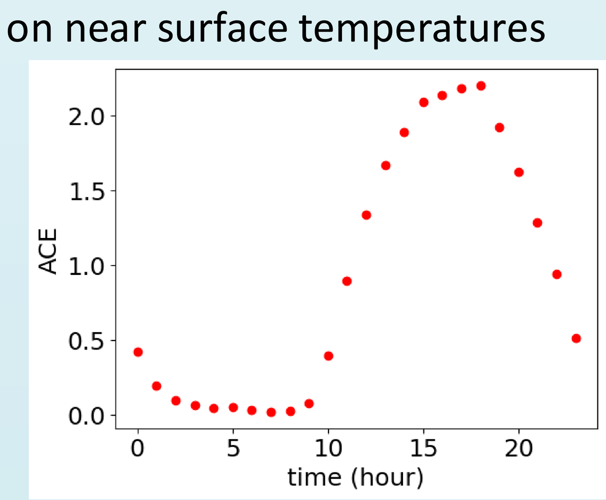

Figure 1. Average ACE Over Time

ACE was averaged over all time steps and increases during peak sunlight hours, with t = 0 corresponding to 8 PM.

Methods

Chelsea Case

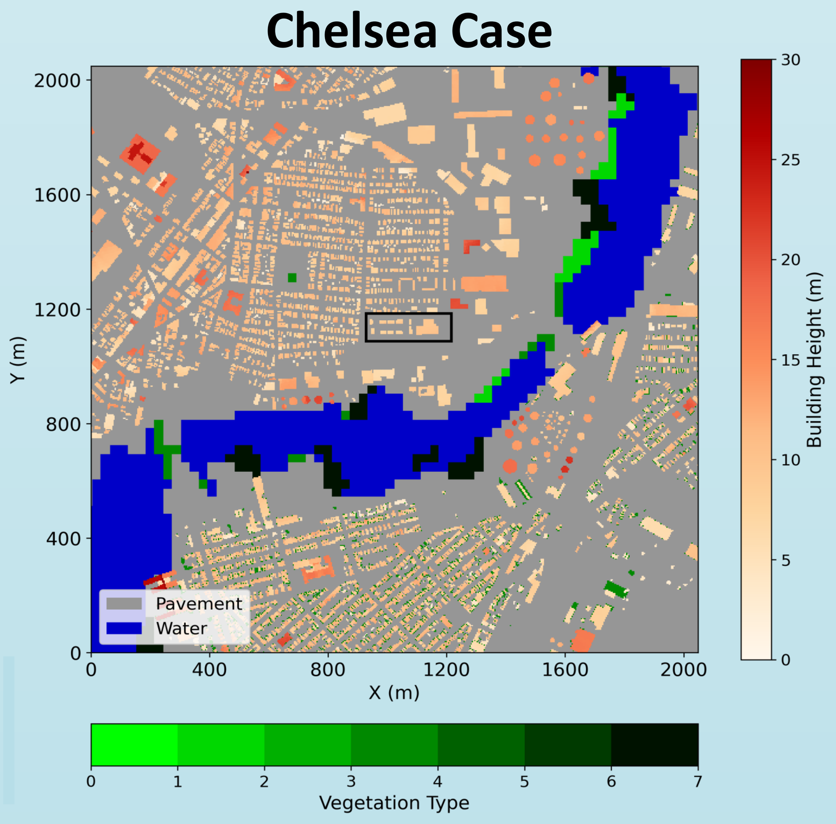

Figure 2. Topography Map for Chelsea Case

- Ran PALM simulations for 0.2, 0.3, 0.5, and 0.7 Albedo, measuring temperature and wind velocity across time and elevation
- Investigated effects of albedo change on temperature and wind velocity

Allston Case

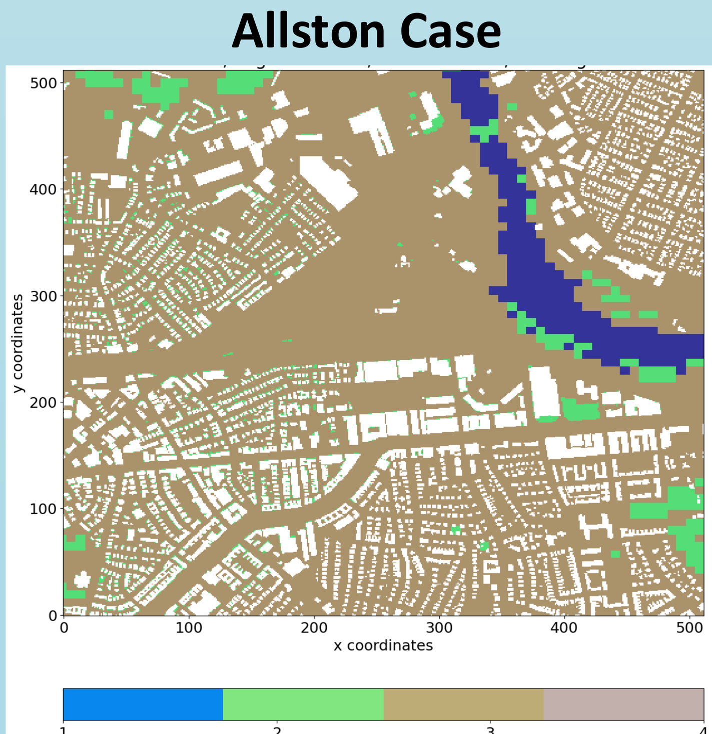

Figure 3. Topography Map for Allston Case

Water = 1, Vegetation = 2, Pavement = 3, Building = 4

- Ran PALM simulations measuring Heat Flux, SW_{in}, LW_{out}, and surface temperature

Usually, ACS is defined as

$$ACS = \frac{ACE}{SW_{in}} = \frac{-\Delta T}{\Delta\alpha \times SW_{in}} \times \frac{total\ area}{building\ area}$$

but SW_{in} is hard to measure.

So, we convert it in terms of heat flux:

$$ACS = \frac{1}{\lambda_H + \lambda_{LE} + \lambda_G + \lambda_{ELW}} \quad \textit{Equation 1}$$

where each λ is a slope of linear relations of sensible, latent, ground heat flux and emitted long wave radiation respectively to temperature, assuming SW_{in} is constant.

Results

Chelsea Case:

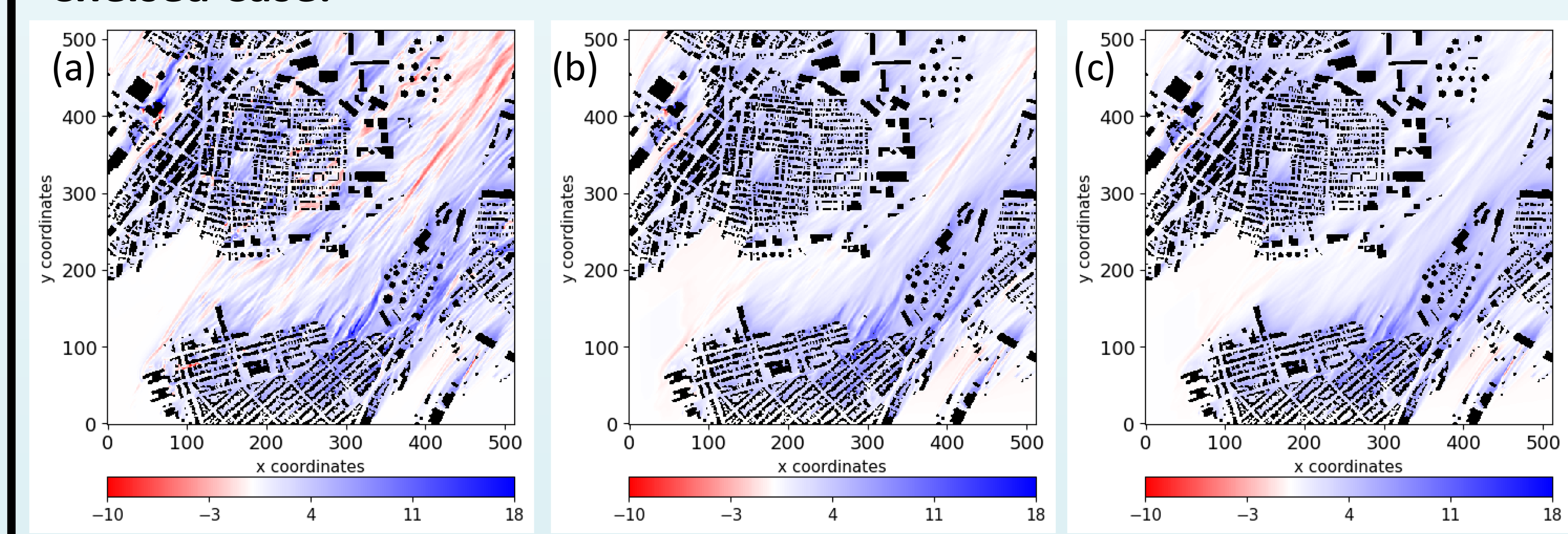

Figure 4. Albedo Cooling Effectiveness (ACE) Between Different Albedo Values at 12PM

(a) shows ACE between 0.2 to 0.3 α, with an average of 0.3427K/α. (b) shows ACE between 0.2 to 0.5 α, with 0.3387 K/α as average. (c) shows ACE between 0.2 to 0.7 α, with an average of 0.3511 K/α

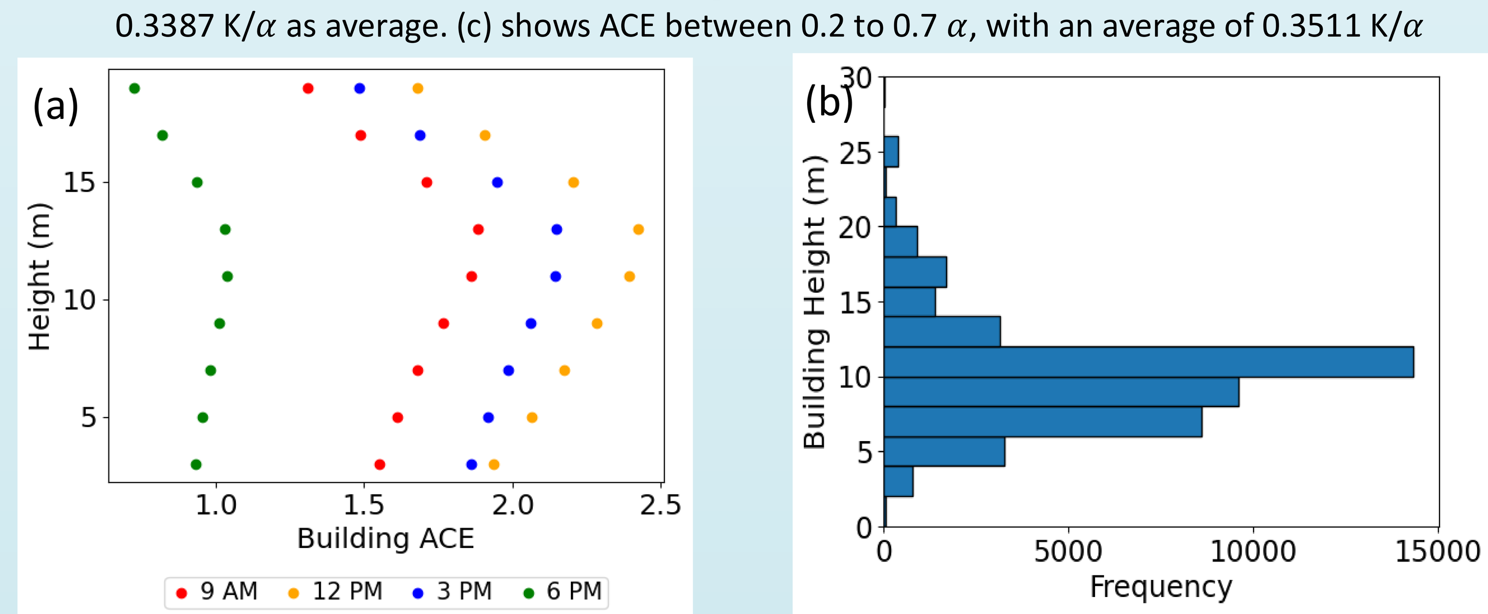

Figure 5. ACE Averaged Over Height and Different Times

$ACE = \frac{-\Delta T}{\Delta\alpha} * \frac{total\ area}{building\ area}$. It is used to investigate effects of albedo change for buildings specifically as white roofs are only being applied to buildings.

Z(a) shows Building ACE plotted against height and different time. Z(b) shows building height distribution.

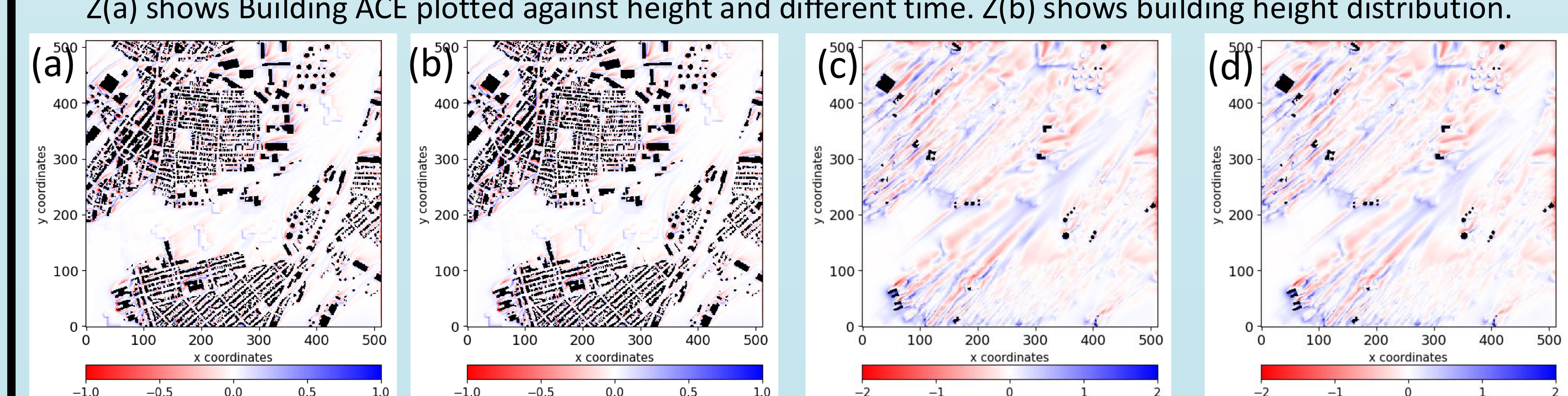

Figure 6. Vertical Wind Velocity in m/s

(a): 0.2 α at h = 1m (b): 0.7 α at h = 1m (c): 0.2 α at h = 19m (d): 0.7 α at h = 19m. Measurements Taken at 12 PM

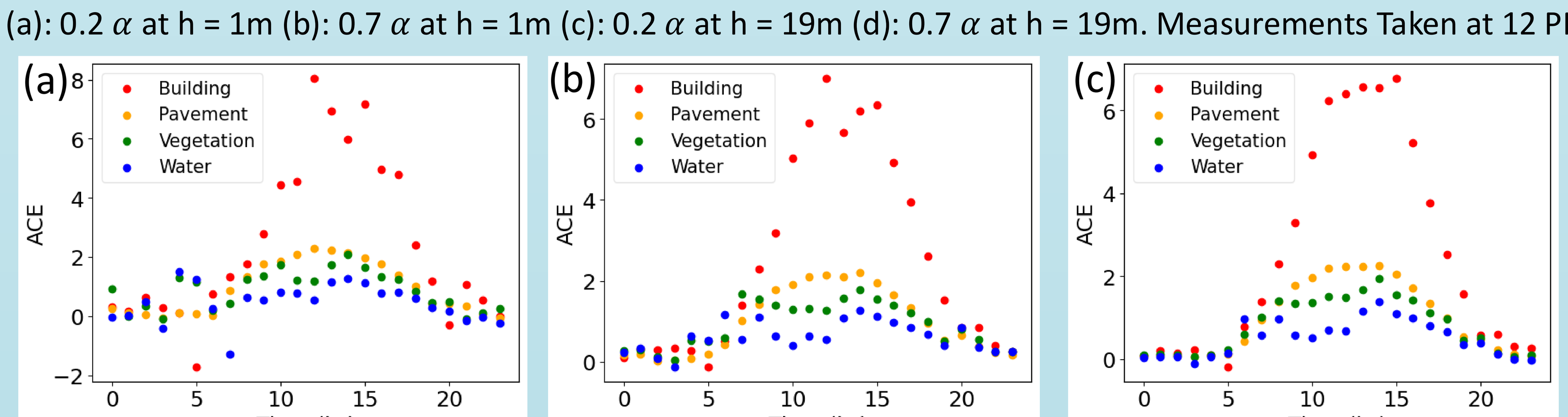

Figure 7. ACE Averaged Over Different Surface Types as a Function of Time at h = 1m

(a): ACE between 0.2 to 0.3 α (b): ACE between 0.2 to 0.5 α (c): ACE between 0.2 to 0.7 α. t = 0 represents 8 PM

Allston Case:

GHF: Ground heat flux
Represents heat absorbed

SHF: Sensible heat flux
Heat being released to atmosphere

QSWS: Latent heat flux
Heat being released as result of evaporation

LWOUT: Long wave out
Outgoing infrared radiation

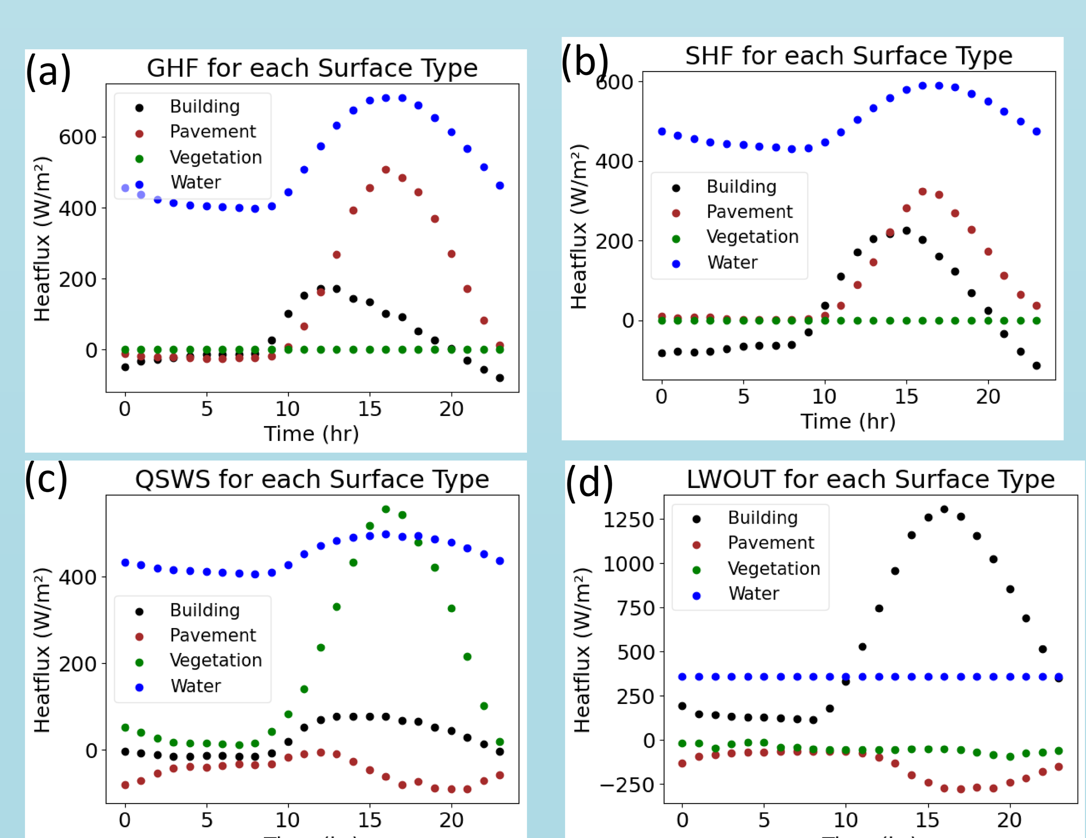

Figure 8. Surface Flux Averages Across Time

(a): GHF (b): SHF (c): QSWS (d): LW_{out}

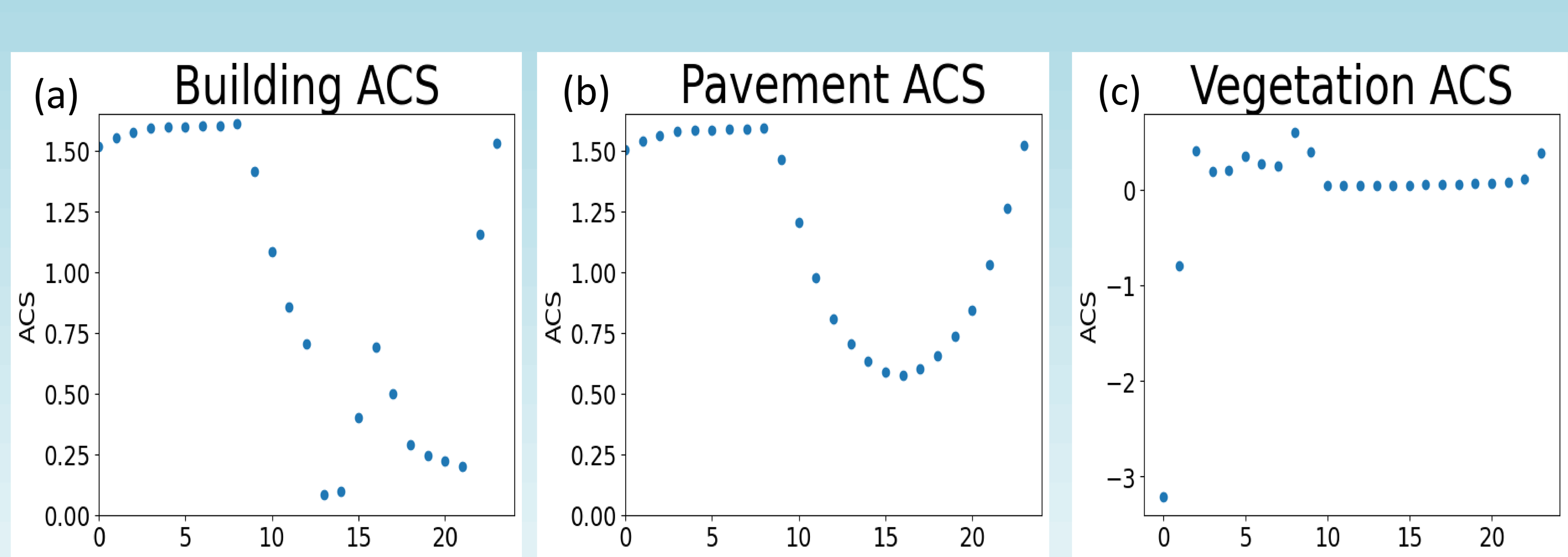

Figure 9. ACS Averaged as a Function of Time for Different Surface Types

(a): Building ACS (b): Pavement ACS (c): Vegetation ACS. T = 0 represents 8 PM

Discussion/ Conclusions

Spatial Variations of ACE (Figure 4)

- Average ACE remains relatively constant but varies strongly spatially
- Small increases in temperature in Figure 4(a) are likely due to turbulence in simulations

Diurnal Cycle of ACE (Figure 5)

- ACE assumes that temperature change is spatially averaged across a large area
- ACE is expected to be strongest near buildings, where albedo changes through white roofs
- Effects stronger around 5m – 15m, where white roofs are concentrated (Figure 5(b))
- ACE is maximized during peak sunlight hours following the diurnal cycle of radiation

Vertical Wind Velocity (Figure 6)

- Note there is no significant difference in vertical wind velocity as albedo changes (Figure 6(a-d))
- Since temperature changes (less than 0.3°C), and correlation between temperature and wind speed are minimal, wind velocity does not vary much with albedo changes
- However, patterns for $\frac{-\Delta T}{\Delta\alpha}$ are related to wind velocity through convection (Figure 4 & 6)

ACE and Different Surface Types (Figure 7)

- ACE is largely different from buildings and other surface types.
- Even among pavement, vegetation, and water, where albedo changes were not directly applied, differences can be spotted.
- ACE might not be accurate across surface types

Heat Flux Diurnal Cycle (Figure 8)

- Each heat flux from Allston Case is linearized as a function of temperature to calculate ACS from *Equation 1*
- GHF, SHF, QSWS high for water as water absorbs and emits heat significantly and releases heat through evaporation
- Pavement (asphalt) absorbs and releases heat significantly as it increases temperature rapidly
- Vegetation releases heat through evapotranspiration

ACS for Each Surface Type (Figure 9)

- Slopes of heat flux used to calculate ACS for different surface types
- Both building and pavement ACS are higher than vegetation ACS
- As expected as buildings and pavements absorb and emit more heat than plants, contributing to urban heating
- ACS captures individual qualities of each surface type better as heat flux depends on surface properties
- With ACS, urban climatologists can better understand effects of surface types and albedo on urban heating

References

1. Li, D. Bridging the Gap Between Applied Meteorology and Climate Science: A White Roof Example. *ARC Geophysical Research* **2025**, *1*.
2. Wang, L.; Huang, M.; Li, D. Where are white roofs more effective in cooling the surface? *Geophys. Res. Lett.* **2020**, *47*, e2020GL087853.

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