URBAN FORM, URBAN HEAT ISLAND EFFECT, AND ENERGY DEMAND :INSIGHTS FROM SEOUL, SOUTH KOREA

Analyzing the Influence of Urban Form Elements on the Urban Heat Island (UHI) Effect and Building Energy Performance in a High-Density Urban Context

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Graduation Thesis

P5 Presentation

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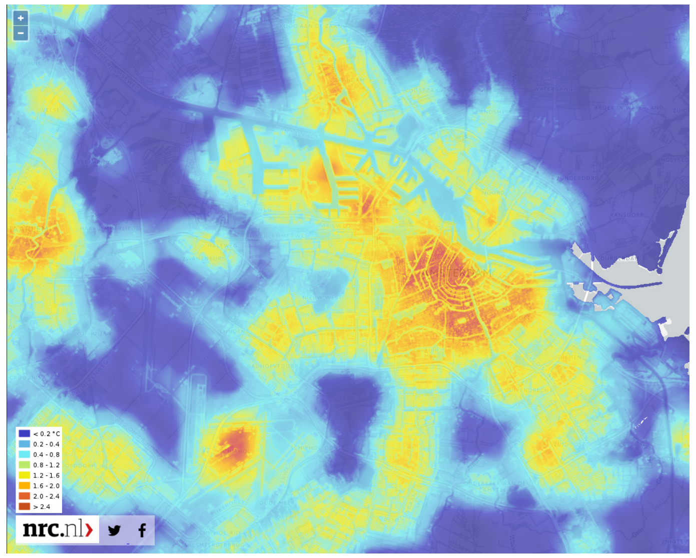
Problem Statement

Better services & infrastructure

Economic opportunity

Urbanization

Rapid changes in UFE



Urban Heat Island (UHI) Effect

- Decreased Quality of Life
- Economic Impact
- Environmental Impact
- **Building Energy Performance**

: A phenomenon where urban areas experience significantly higher temperatures than surrounding suburban and rural areas due to human activities, dense infrastrucutre and reduced vegetation (Park et al., 2016)

United Nations (UN) "68% of the world population projected to live in urban areas by 2050" → Evidence-based strategy is required

Goal of the Research

1. Converting Land Surface Temperature to Air Temperature

2. Finding Correlation between Urban Form Elements, Air Temperature and Energy Consumption

Main Research Question

"How do Urban Form Elements influence the Urban Heat Island effect and Building Energy Performance in a selected area of Seoul, South Korea?"

What is the novelty of my research?

Long-Term Analysis

Cascade Effects

Seasonal Anlysis

Scale Analysis

Research Area - Seoul, South Korea

Began in the 1960s due to rapid urbanization and industrialization

Experiencing UHI Effect

Data Availability

More than 10 years worth of data for Weather (AWS) and Energy Demand (Electricity & Gas)

Diverse Urban Form Elements

High-rise to Low-rise buildings across the districts and several major urban parks

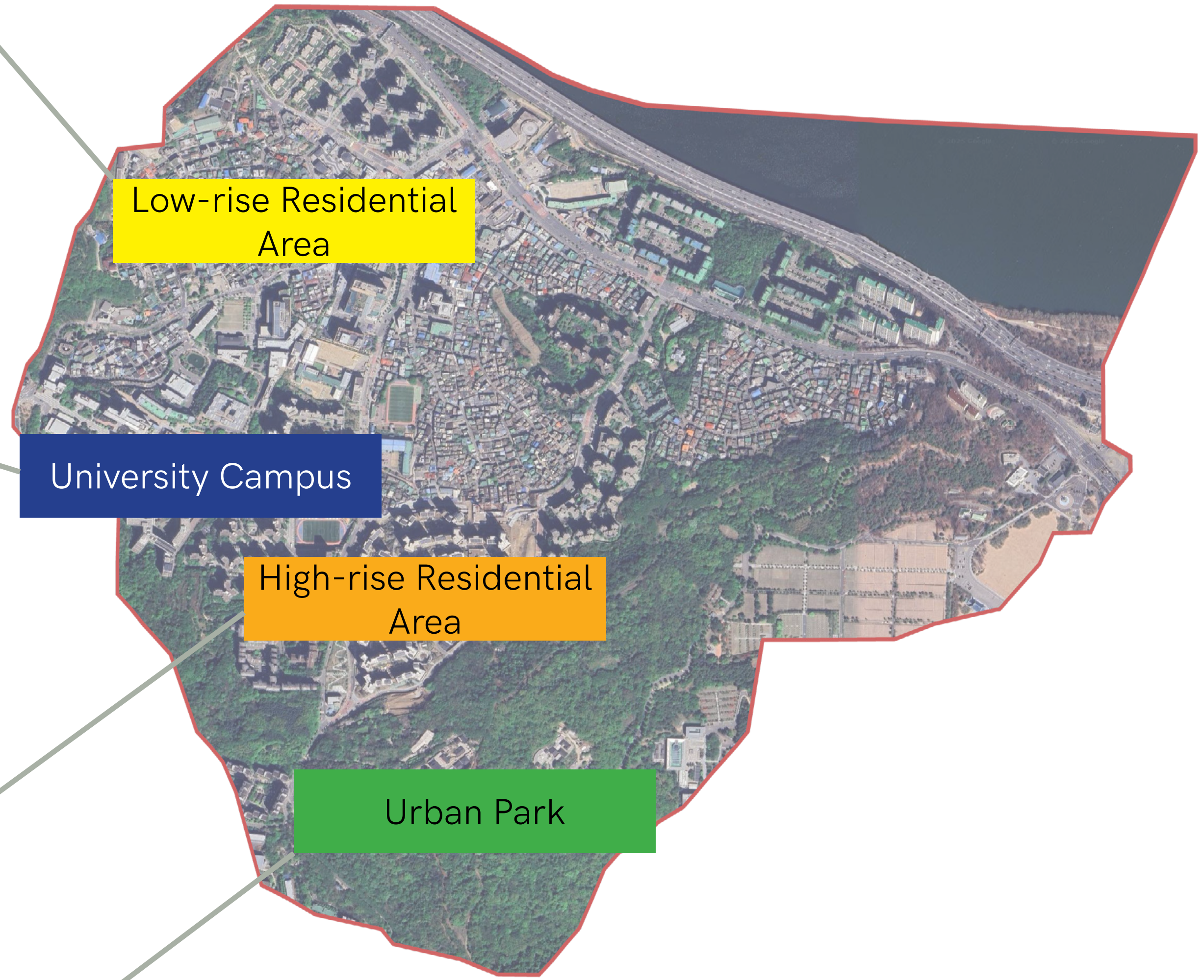
Research Area - Heukseok-dong, Seoul

Old and Low-rise Residential Area

Chung-Ang University Campus

New and High-rise Residential Area

Dalma Park



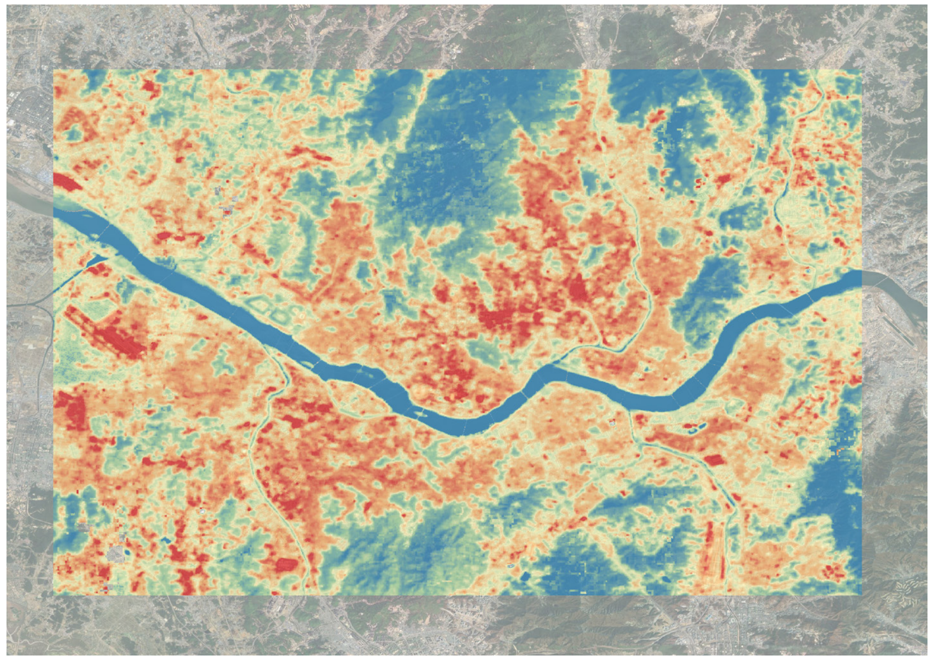
Heukseok New Town Project
(Redevelopment Promotion Project)

Temperature Data Acquisition Method

Spatially Continuous Land Surface Temperature

Point Air Temperature

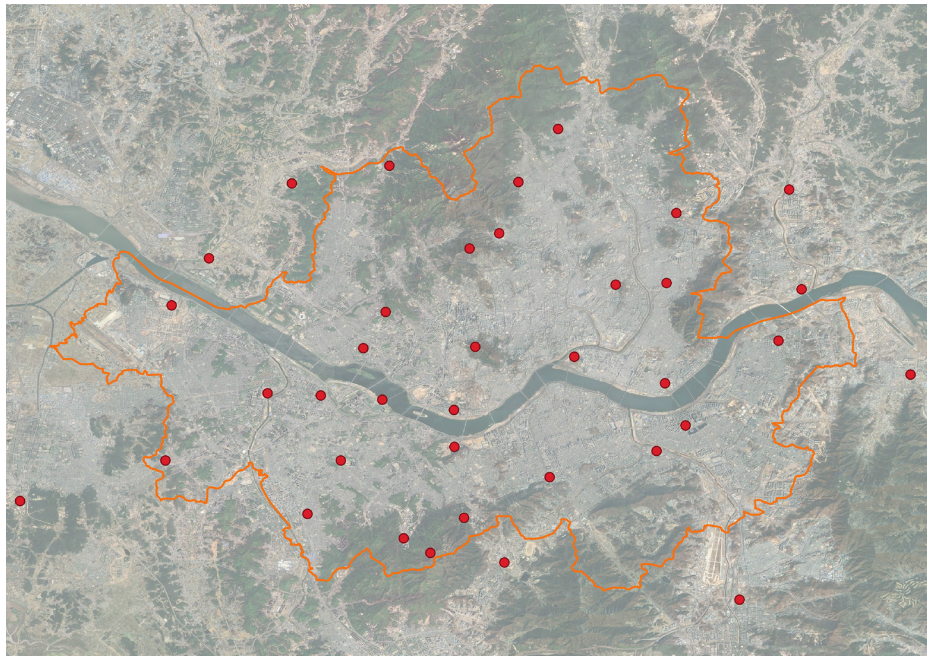
Satellite Image



Low Temporal Resolution

Very High Spatial Resolution

Automatic Weather Station (AWS)



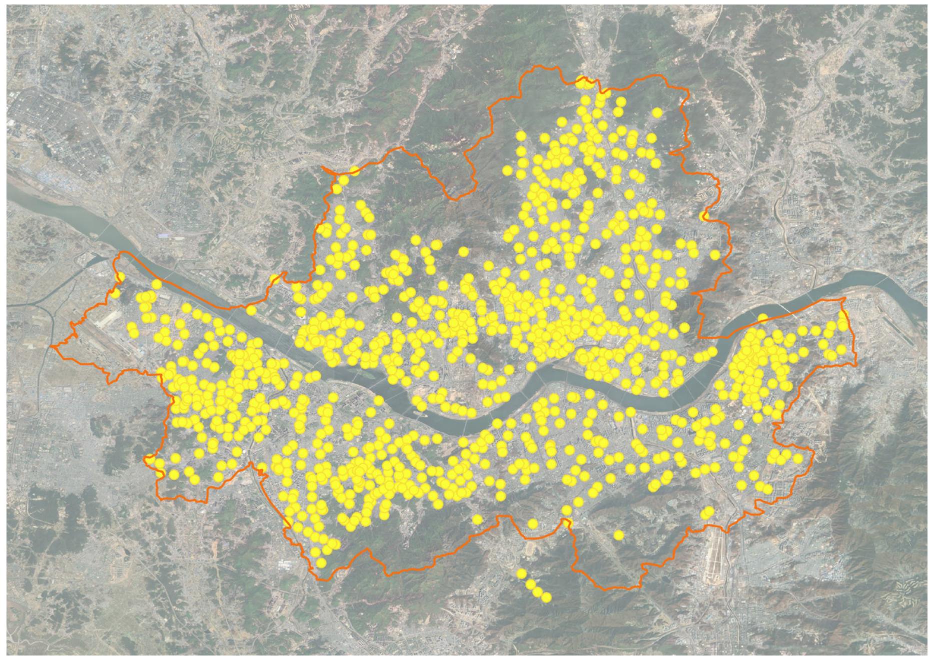
39 Automatic Weather Stations

High Temporal Resolution

Low Spatial Resolution

Measure Every Minute (1997~)

S-DoT Sensor



1159 S-DoT Sensors (2024)

Available from 2020

High Spatial Resolution

Measure Every Hour

Known Systematic Temperature Difference - Urban Heat Island Effect

S-DoT Sensors' air temperatures are about 1.8°C higher than AWS (May - August, 2020)

Temperature Types

Temperature

Land Surface Temperature (LST)

Radiative skin temperature of uppermost layer of the Earth's surface

Air Temperature (AT)

Temperature measured at 1.5-2 meters above the surface

Why Air Temperature ?

Building HVAC systems operate based on air temperature measurements — *Xiong et al. (2023)*

All standard thermal comfort indicies rely on air temperature measurements — *Su et al. (2021)*

3D geometry structures significantly affect air temperatures than LST — *Voogt and Oke (2003)*

↓

Energy Consumption of Buildings

Obtaining Air Temperature Distribution Methods

Simple Statistical Method

Linear Regression (LR)	*Assume LST and AT have linear relationship*	*Meyer et al. (2016)*
Multiple Linear Regression (MLR)	*Linear relationship but incorporate additional predictors*	*Noi et al. (2017)*

Geostatistical Method

Regression Kriging	*Combine regression analysis with spatial interpolation*	*Ding et al. (2023)*

Tree-based Method

Random Forest (RK)	*Building multiple decision trees using predictors*	*Tang et al. (2021)*

Neural Network

Multi-Layer Perceptron (MLP)	**TEMLI Method (non-linear relationships)**	*Salih et al. (2025)*
Artificial Neural Network (ANN)	*Captures non-linear relationships between LST and AT*	*Choi et al. (2021)*

Methodology Choice

Comparative Performance

Category	Method	Study	R^2	RMSE (°C & K)	Key Advantage	Limitations
Statistical method	Linear Regression	Meyer et al. (2016)	0.78	5.83	Simple interpretable	Cannot handle nonlinear relationships
	Multiple Linear Regression	Noi et al. (2017)	0.93/0.80/0.89	1.5/2.0/1.6	Good baseline performance	Limited in spatial variations
Geostatistical method	Regression Kriging	Ding et al. (2023)	0.95	0.92	Smooth air temperature variation	Assumes linear relationships in trend
Tree-based methods	Random Forest	Tang et al. (2021)	0.96-0.98	1.48-2.55	Handles multiple variables	Creates artificial spatial patterns
Neural Network	**MLP (TEMLI)**	Salih et al. (2025)	0.91	1.5	Superior in extreme conditions	Requires substantial training data
	Artificial Neural Network (ANN)	Choi et al. (2021)	0.98	2.19	Capture complex relationships	Highly dependent on input variables

Why Multi-Layer Perceptron?

Approved methodology with high R^2 and low RMSE

LST and AT have complex non-linear relationships

Including diverse environmental variables is valuable *Choi et al. (2021)*

Satellites Availability

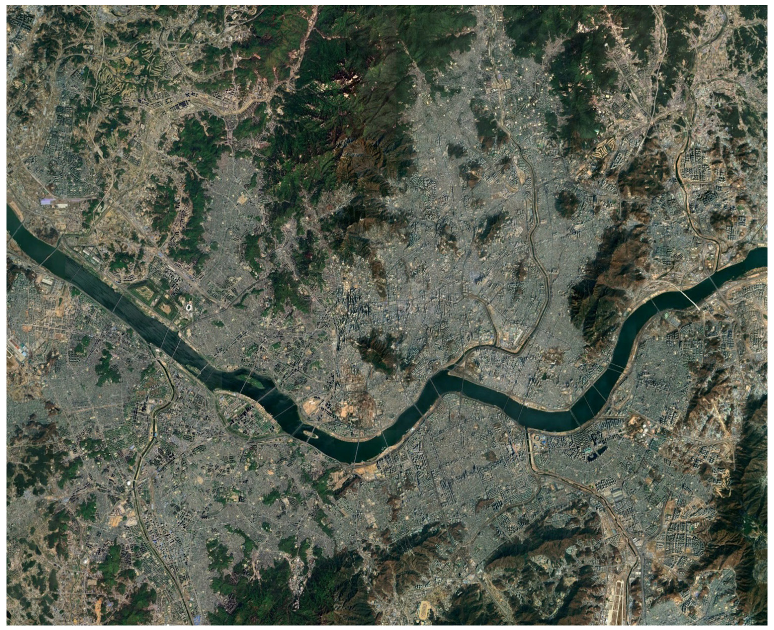
Satellite	Spatial Resolution	Temporal Resolution	Spectral Bands	Years of Operation
Landsat	**30m**	**16 days**	**11 bands (2 thermal)**	**2013 - present**
MODIS	1000m	Daily	36 bands (16 thermal)	1999 - present
ASTER	90m	16 days	14 bands (5 thermal)	1999 - present
Sentinel-3	1000m	2 days	11 bands (3 thermal)	2016 - present
ECOSTRESS	70m	5 days	6 bands (5 thermal)	2018 - present

10 years worth of data

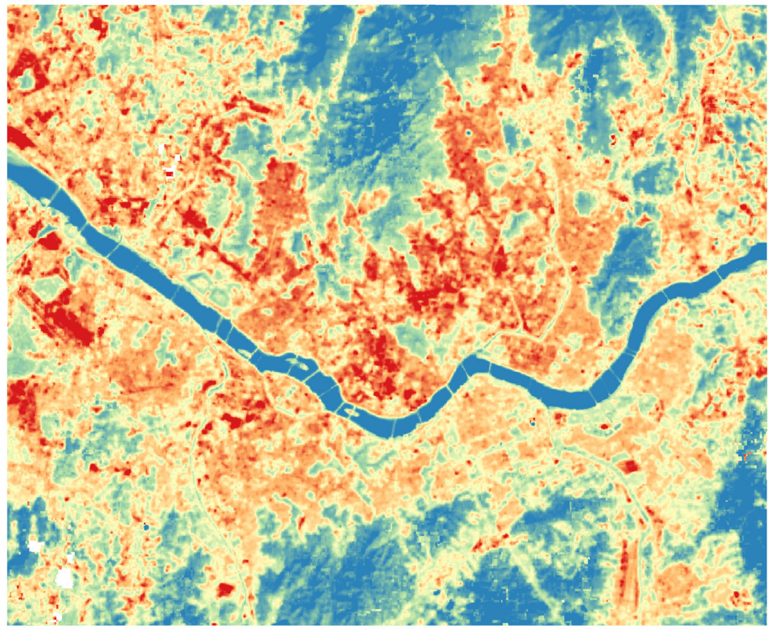
High spatial resolution

Most widely used platform for LST *(De Almeida et al., 2021)*

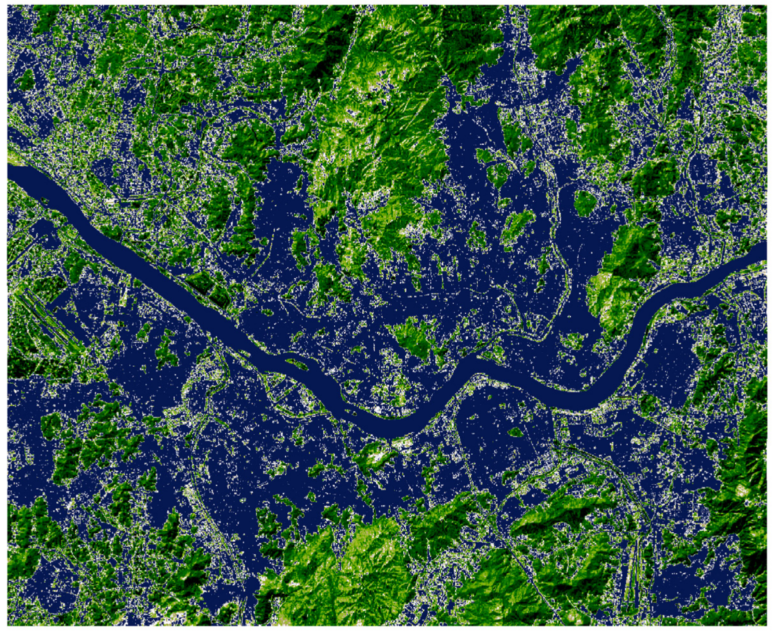
→ Landsat 8



Seoul Satellite View



Seoul LST



Seoul NDVI

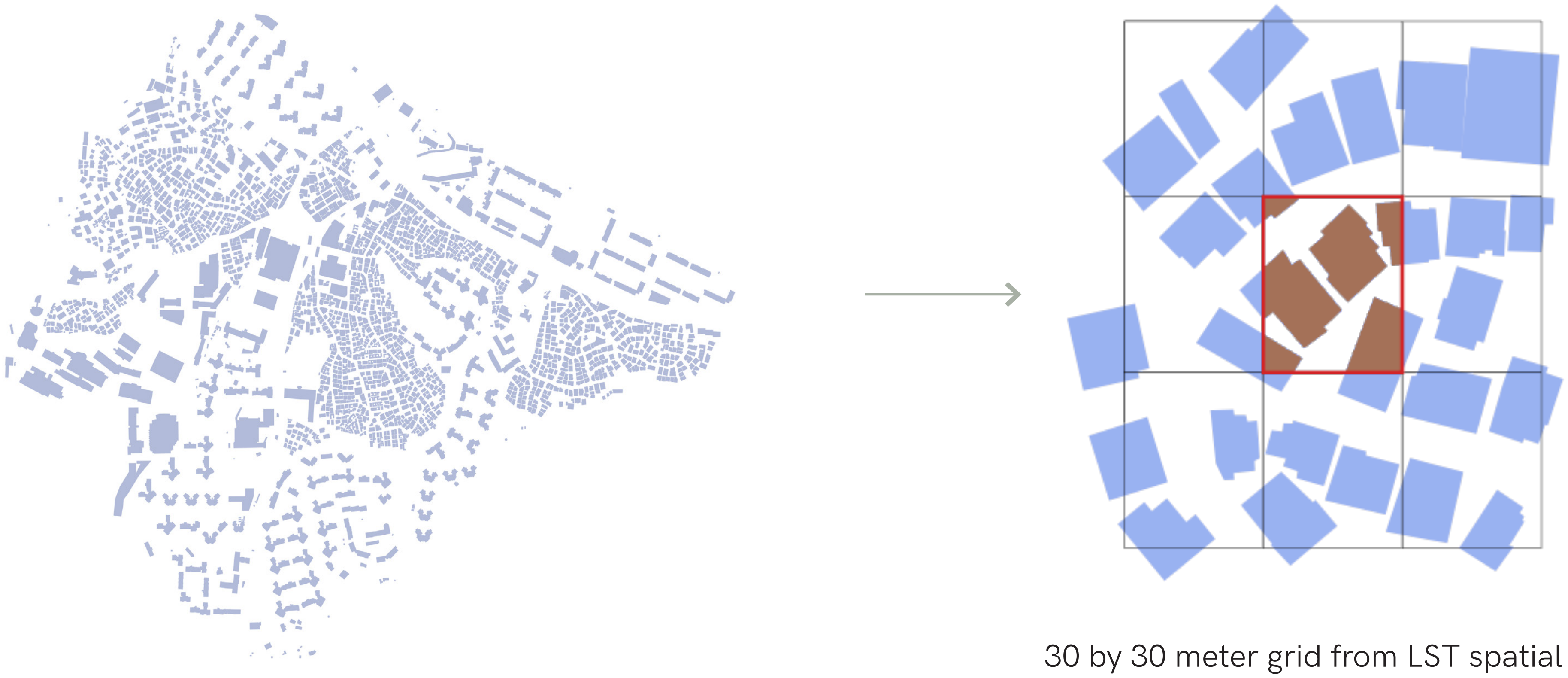
6 Urban Form Elements

No.	Urban form element	Description	Measure
1	NDVI	Normalized difference vegetation index	Derived from the Landsat
2	Building ratio	The ratio of building in a grid cell	The ratio of total building space in a grid cell
3	Weighted height	Height of buildings account for size and footprint of buildings	Weights each building's height by its footprint area within the grid cell
4	Building volume	The volume of a building	Building height x Building footprint
5	FSI	Floor space index of a building	Gross floor area / Site area
6	GSI	Ground space index of a building	Building footprint / Site area

Available urban form elements from provided data source

Most widely discussed urban form elements in UHI studies *Liao et al. (2021)*

Importance of 3D morphology of the buidlings *D. Wang et al. (2021)*

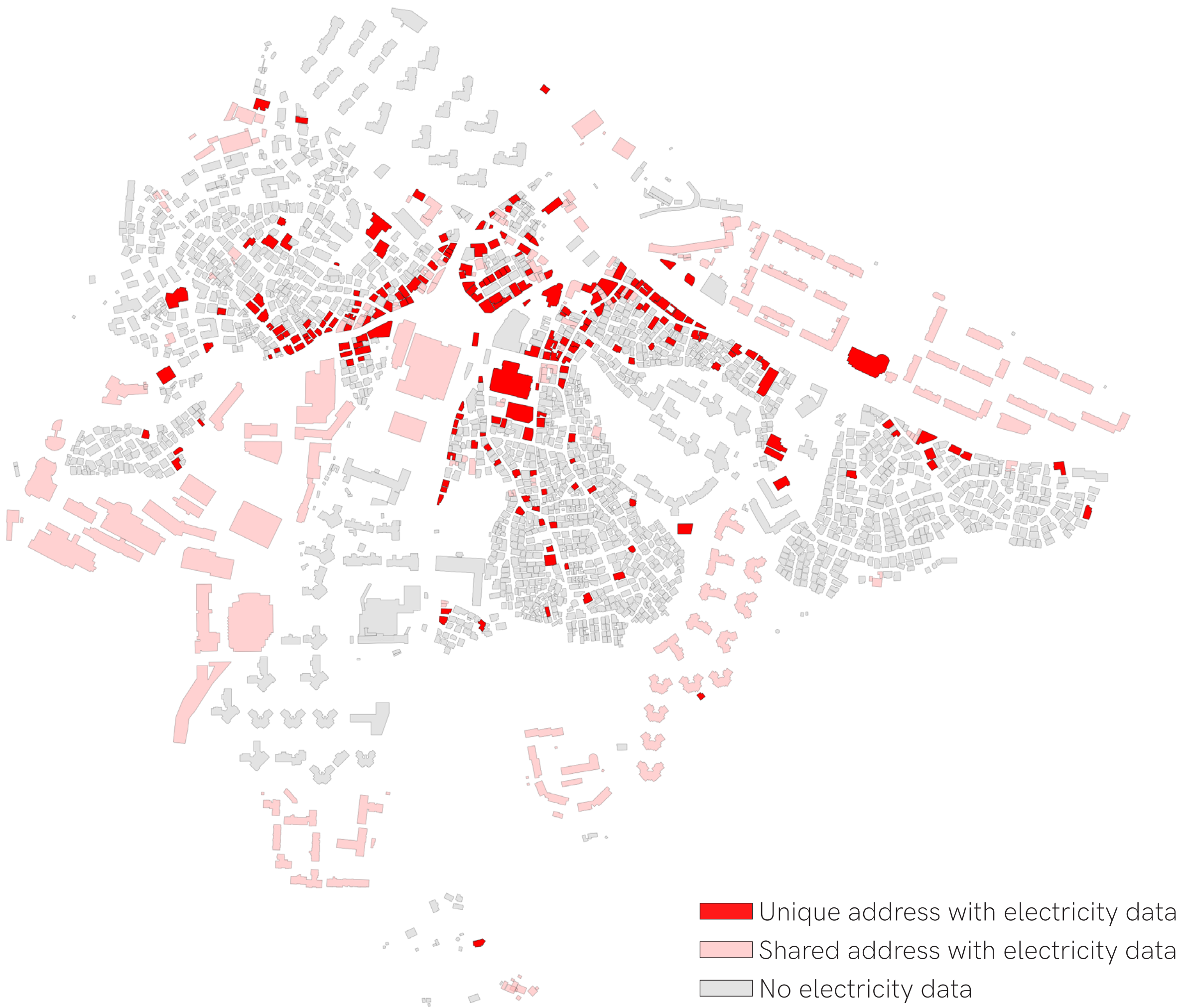


30 by 30 meter grid from LST spatial resolution

Energy Consumption Data

No.	Site location	District code	Neighborhood code	Y/M of use		New address road code	Amount used (kWh)
1	서울특별시 동작구 흑석동 1-3	11590	10500	202008		115903119009	765
2	서울특별시 동작구 흑석동 4	11590	10500	202008		115903119009	9225
3	서울특별시 동작구 흑석동 6-5	11590	10500	202008	. . .	115903119009	18643
4	서울특별시 동작구 흑석동 6-21	11590	10500	202008		115904157413	4379
5	서울특별시 동작구 흑석동 7-1	11590	10500	202008		115903119009	1876
6	서울특별시 동작구 흑석동 8-30	11590	10500	202008		115903119009	5424

Buildings with Electricity Data by Address Type - August 2020



Energy Use Intensity (EUI) (kWh/m²)

Divide total energy consumption by Gross Floor Area (GFA)

Straightforward measure of how efficiently building uses energy

↓

Many buildings shared building address → Same EUI

↓

Buildings with unique building address

↓

Most buildings are low-rise residential buildings

Important Considerations and Assumptions

Limitations of Using Satellite Data

Satellite Orbit Cycle → 1-2 images per month at 11:12 AM of day → Miss critical temperature extremes

Zhou et al. (2014)
Imhoff et al. (2009)
→ Acknowledge limitations, but no attempting to overcome the limitation

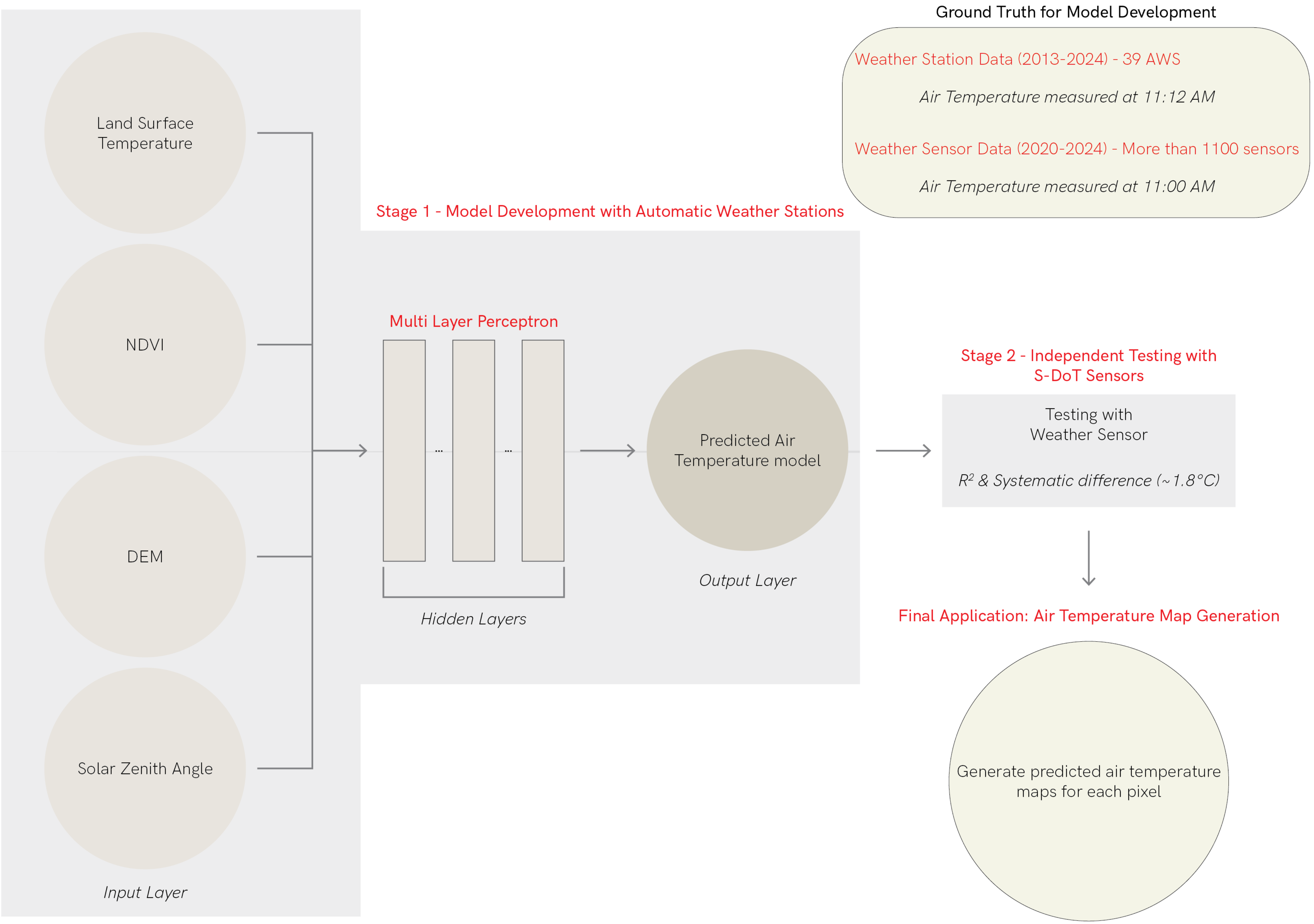
Imhoff et al. (2009) → Concluded this was acceptable for comparative UHI analysis

Temporal Mismatch (Temperature vs Energy Use)

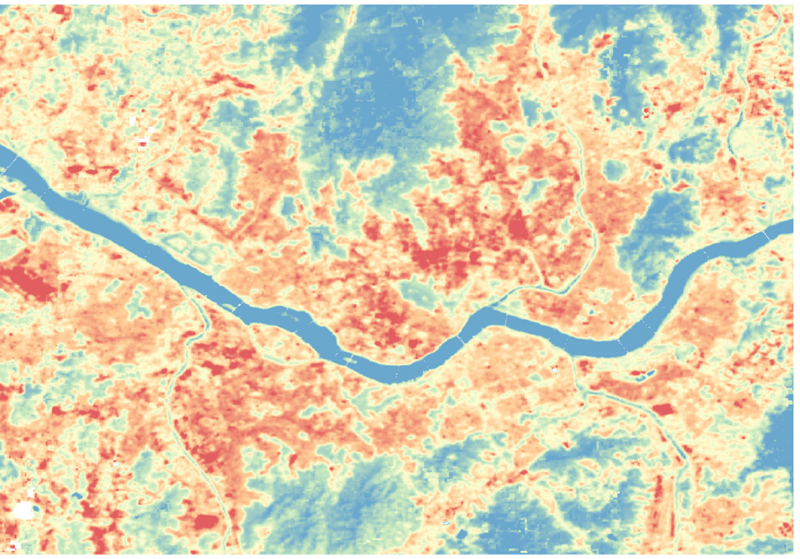
Single Snapshot Temperature at 11:12 AM
Energy Consumption Data is aggregated Monthly
→ Represent the entire month's temperature patterns and energy use

Understanding the relative relationships and long-term trends over 10-year study period

Multi Layer Perceptron Methodology



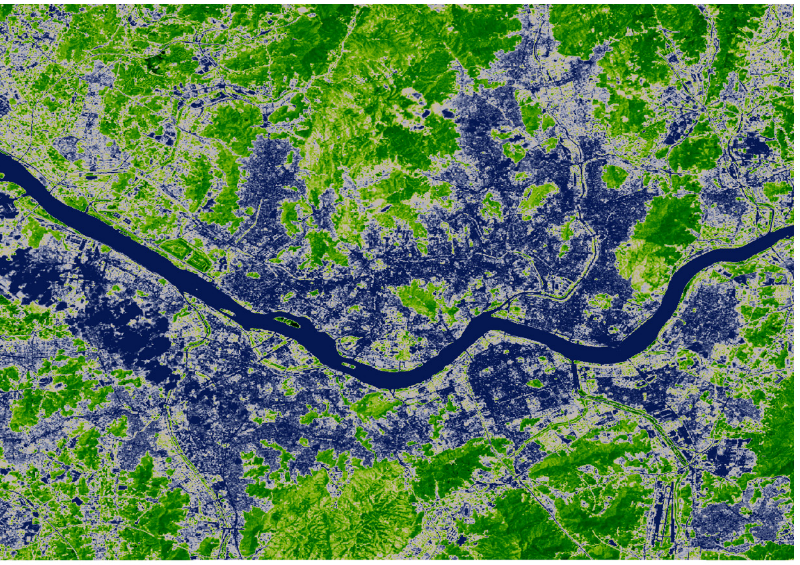
4 Input Features for MLP



Land Surface Temperature (LST)

Thermal information measured by Landsat at 11:12 AM

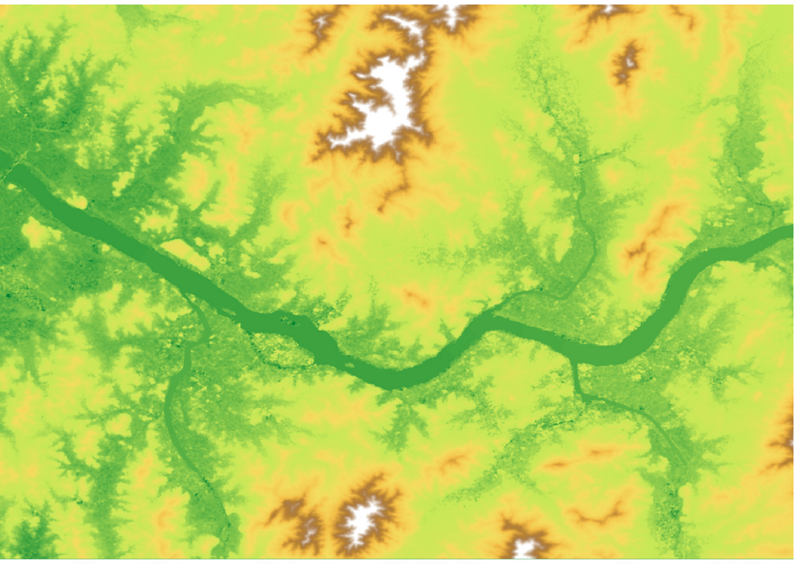
Radiative skin temperature of uppermost layer of the Earth's surface



Normalized Difference Vegetation Index (NDVI)

Significantly affects LST and air temperature relationship through evapotranspiration

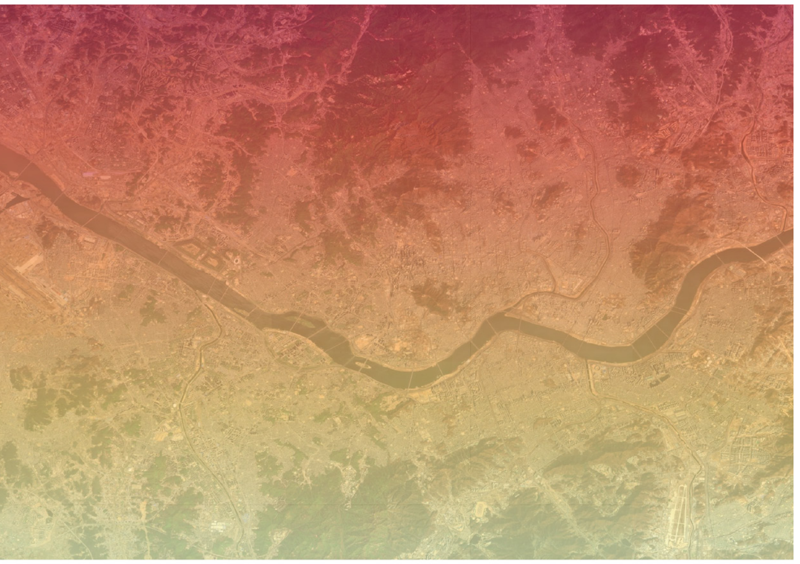
Vegetation's cooling effect



Digital Elevation Model (DEM)

Elevation strongly influences air temperature through the environmental lapse rate

Temperature typically decreases ~6.5°C per 1000m elevation gain

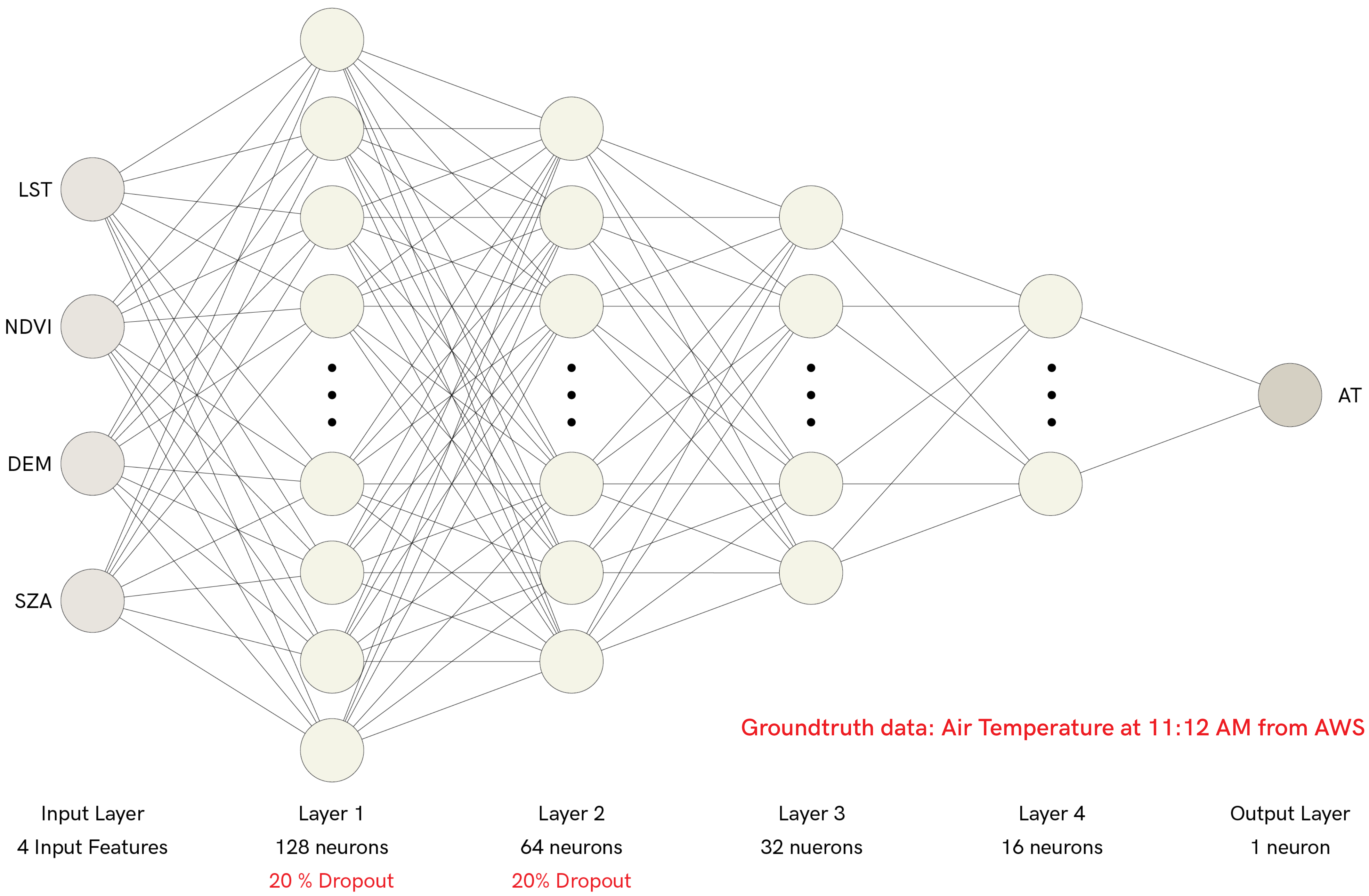


Solar Zenith Angle (SZA)

Angle between the sun and the vertical direction

Intensity of solar radiation

Stage 1: Model Development with Automatic Weather Stations



128 - 64 - 32 - 16 - 1 Funnel architecture

20% Dropout - Prevent overfitting

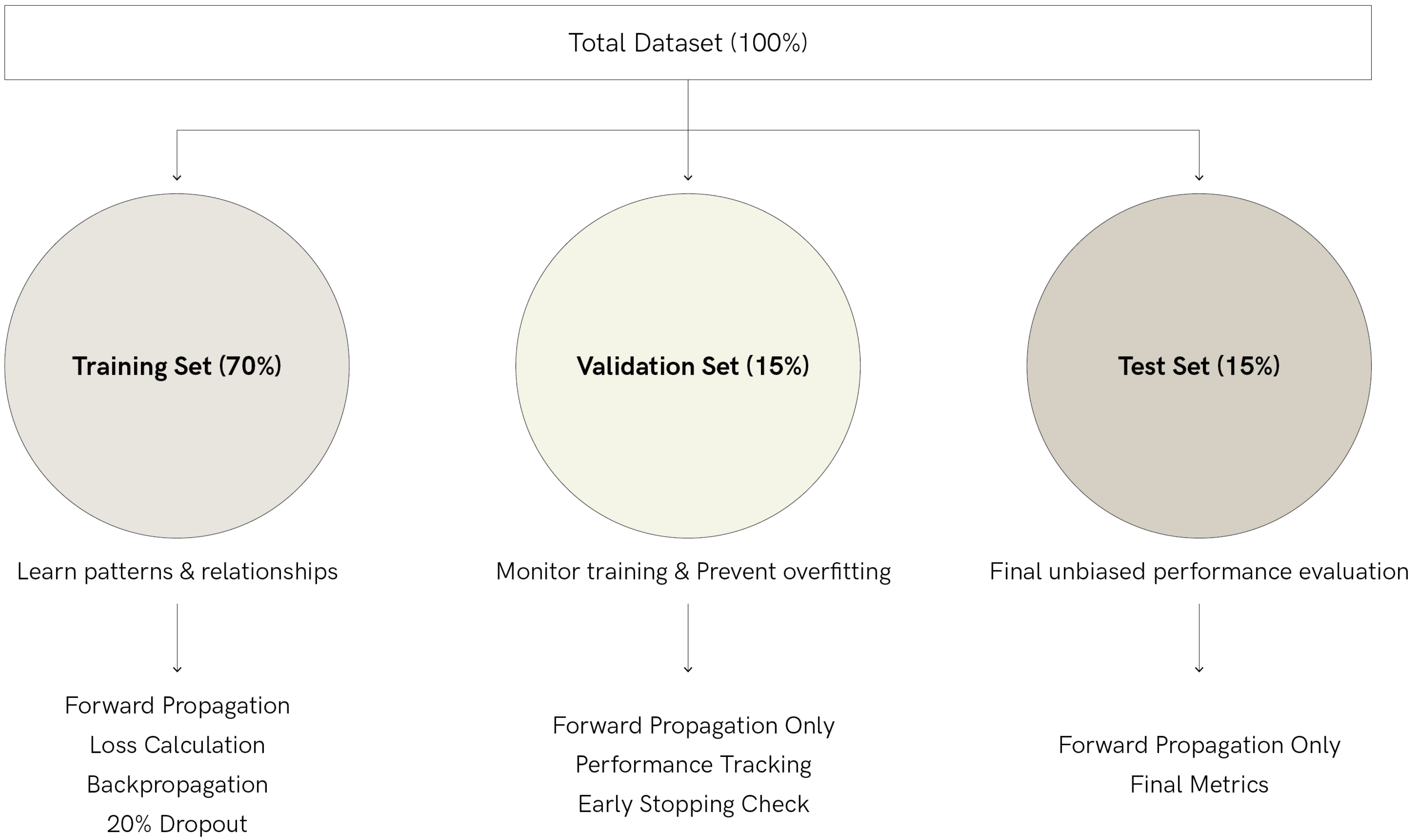
Learning rate = 0.001

Maximum epochs = 200

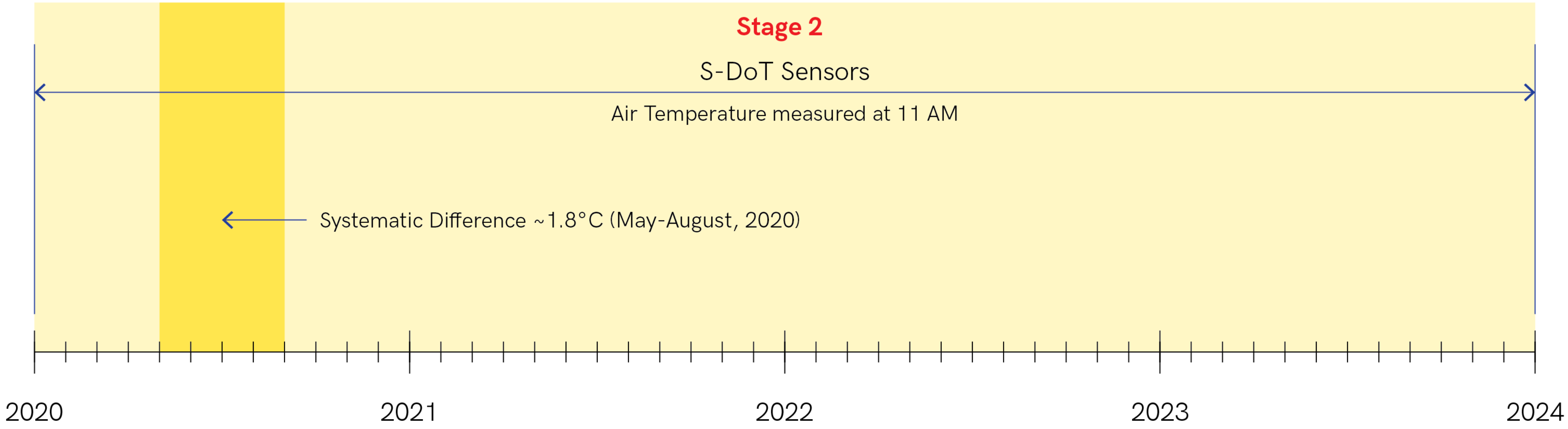
Early stopping patience = 20 epochs

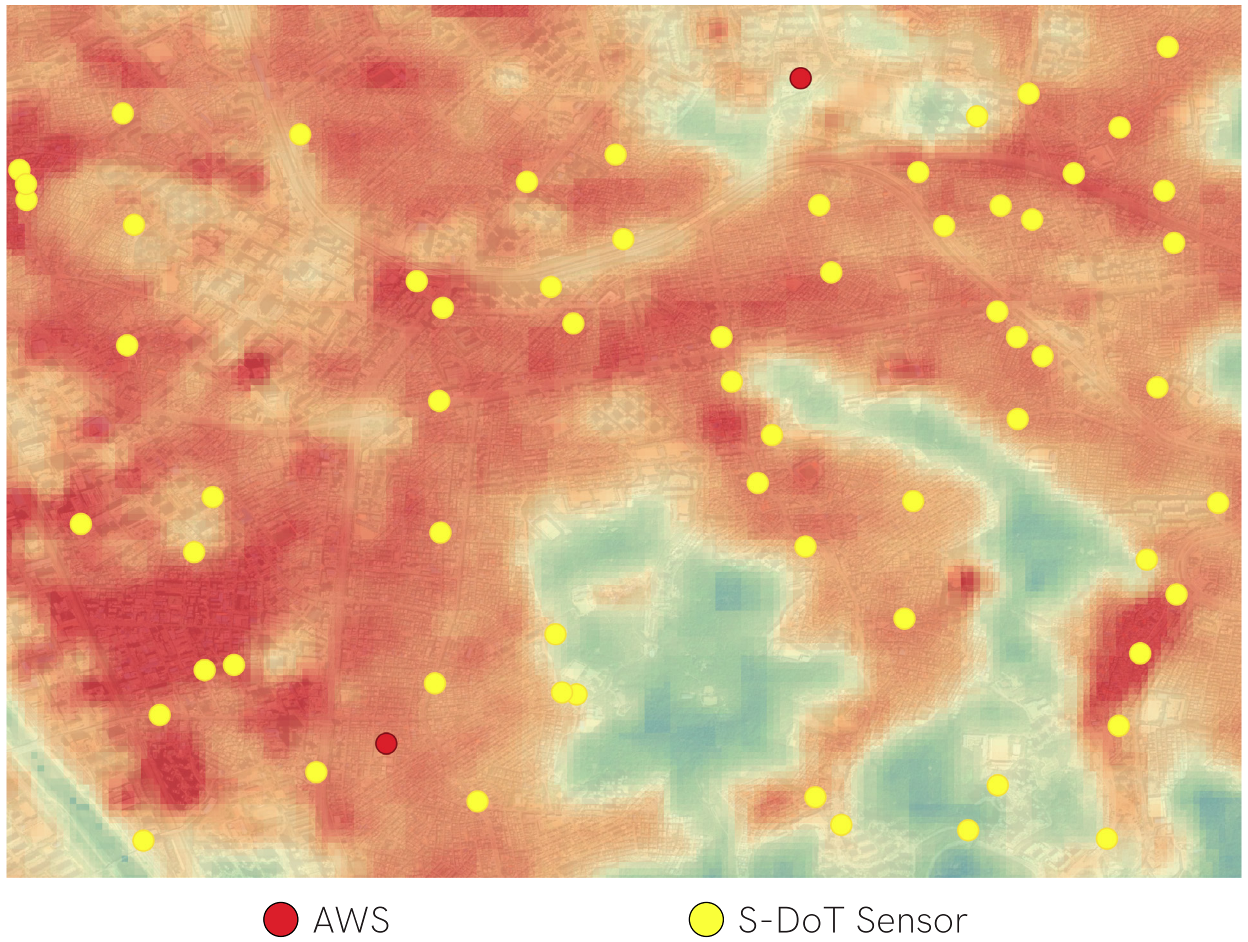
Training set	70%
Validation set	15%
Testing set	15%

Stage 1: Model Development with Automatic Weather Stations



Stage 2: Independent Testing with S-DoT Sensors





S-DoT Sensors are more densely distributed across Seoul

↓

Spatial Validation

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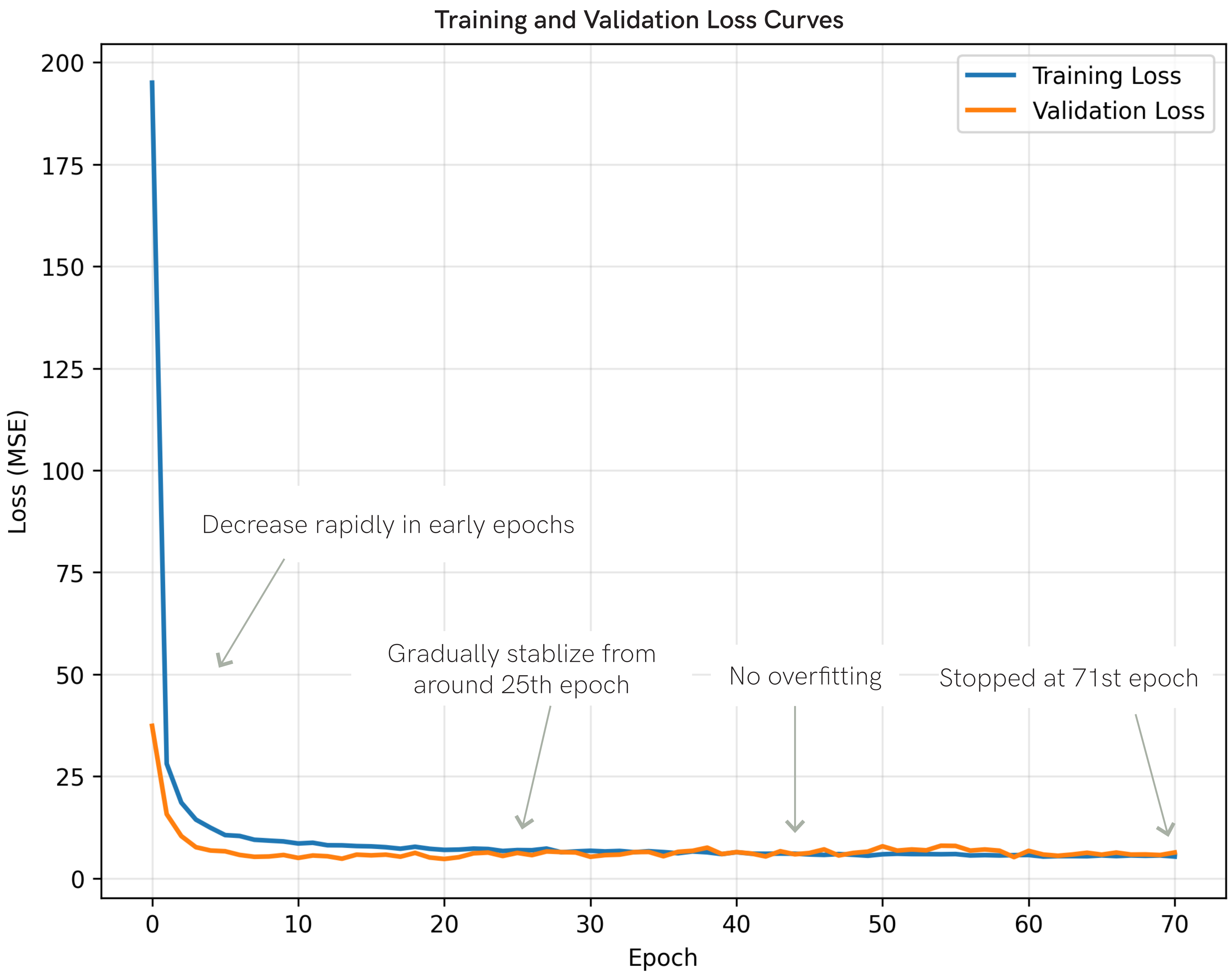
Examine known systematic temperature difference (1.8°C)

Extract the trained model's air temperature predictions at each sensor location

Compare with the actual air temperature measurements

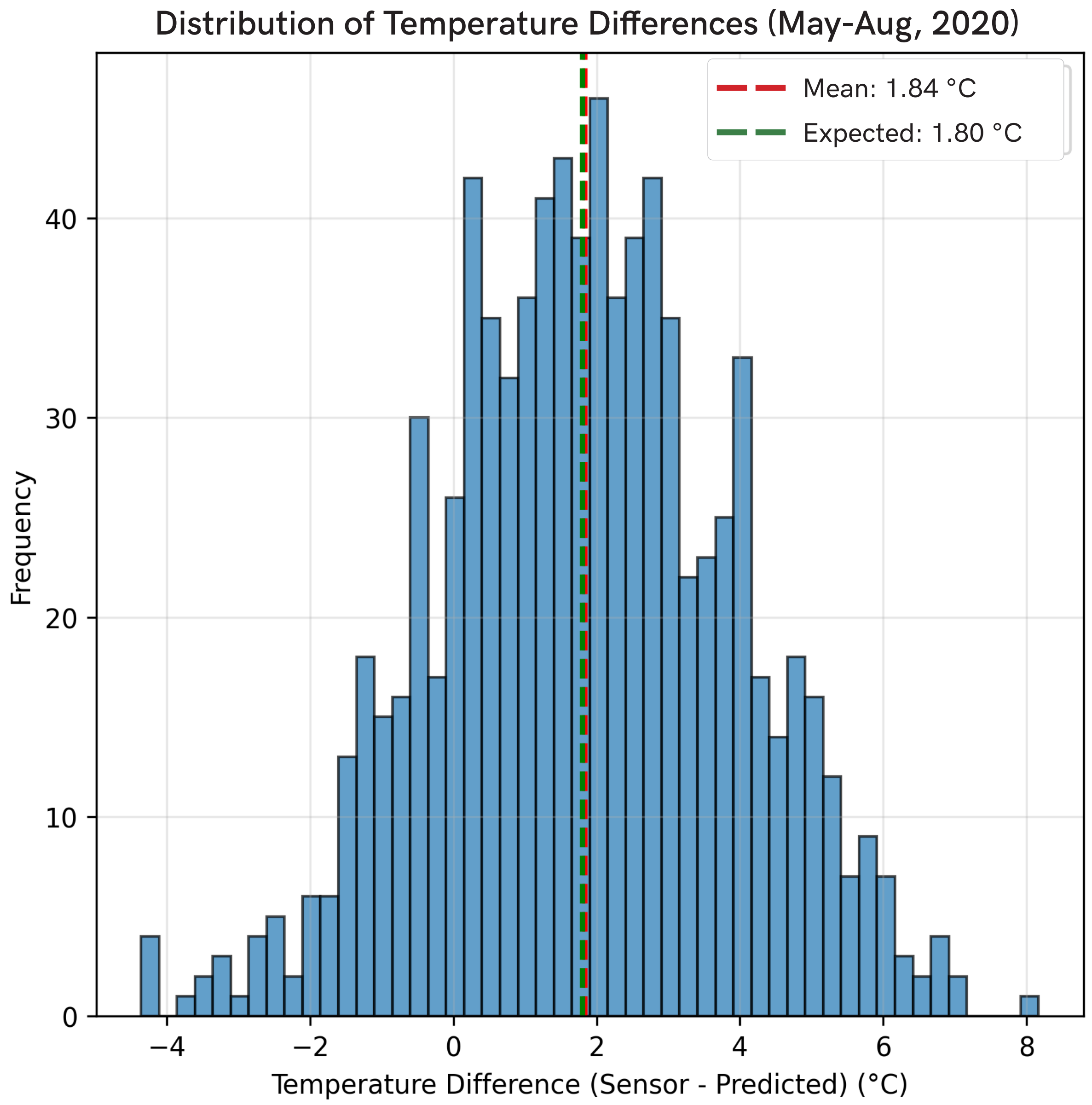
Result - Stage 1: Model Development with Automatic Weather Stations

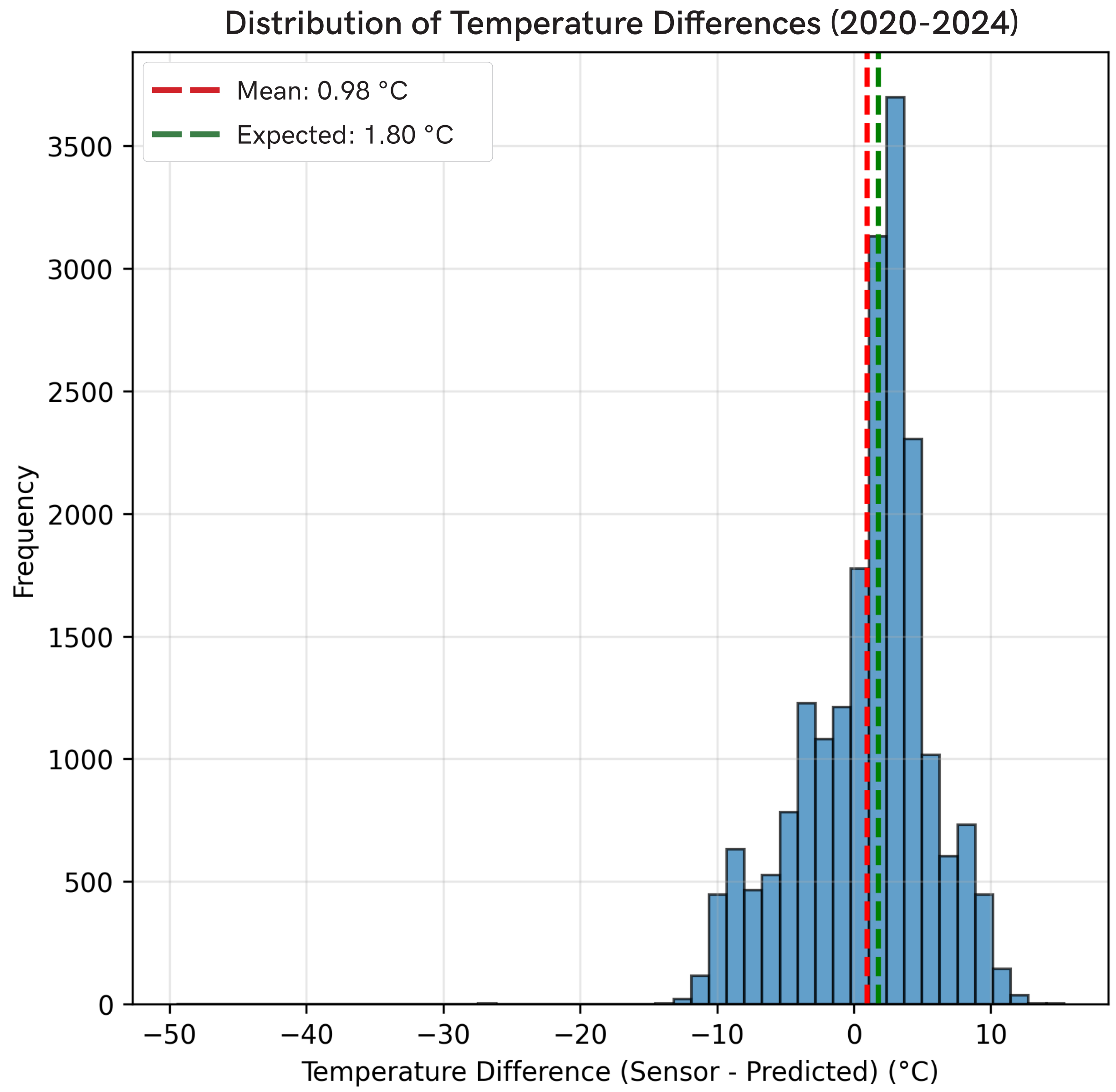


R^2	0.9684
RMSE	2.095 °C
MAE	1.616 °C
CVRMSE	15.50 %

MLP Model successfully learned the pattern between LST and AT

Result - Stage 2: Independent Testing with S-DoT Sensors





Mean Temperature Difference	1.84 °C
R^2	0.653

Mean Temperature Difference	0.98 °C
R^2	0.807

Known systematic difference	1.80 °C
Model's systematic difference	1.84 °C

→ **Approve predictive capability**

Urban Form Elements Importance

Genizi Method

Which urban form elements have the greatest influence on air temperature change? → Relative Importance

Handling Multicollinearity

High NDVI ⟷ Low Building Ratio

FSI ⟷ Building Height

→ Creating confounding effects that obscure the true combination of each variable

Decompose the total R^2 among predictors while **accounting for shared variance** between correlated variables

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Partial Correlation

Does GSI have a negative correlation with air temperature? → Directional Effect

Reveal directional effects of each variable while controlling for all other variables

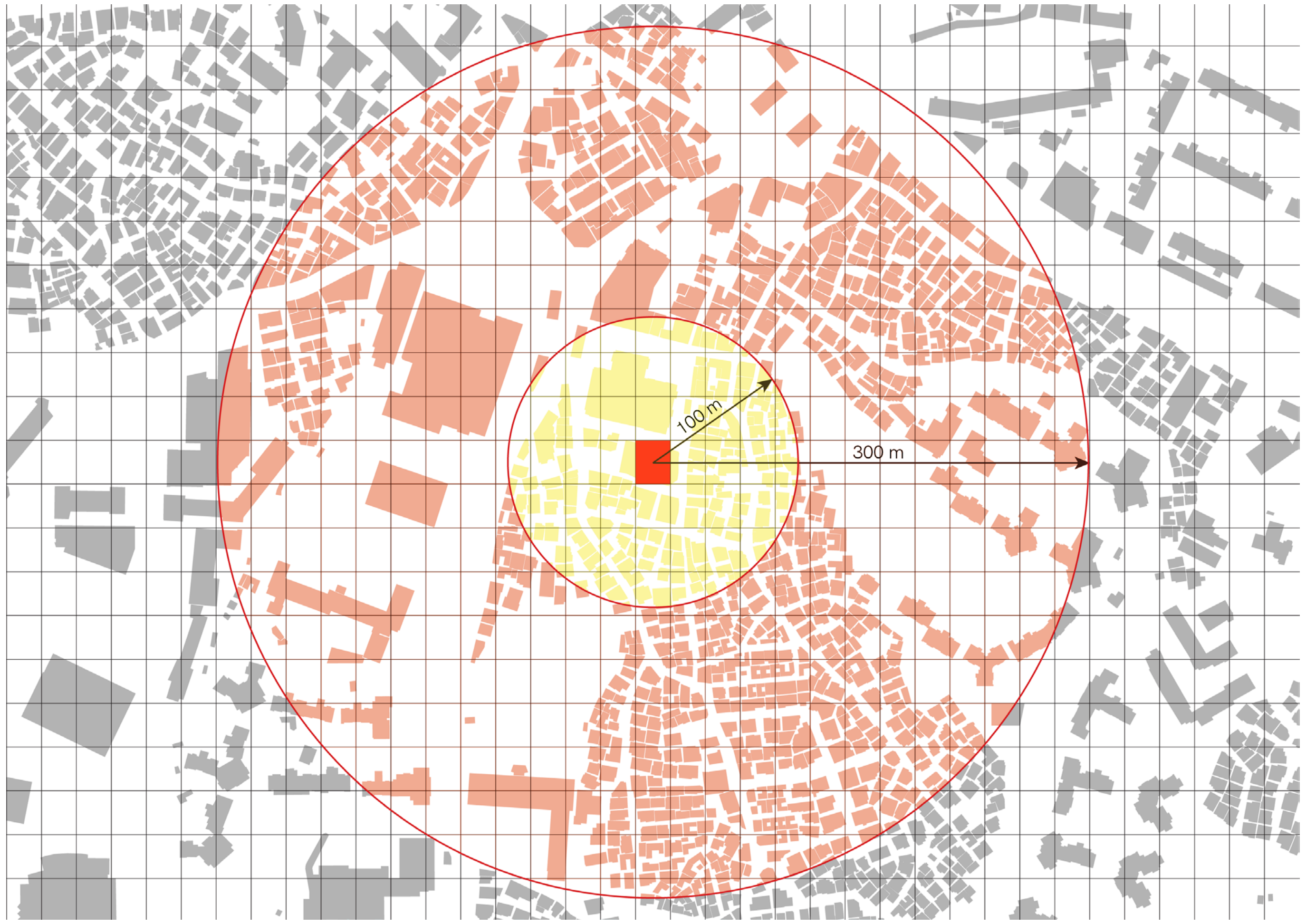
Liao et al. (2021)

Genizi Method + Partial Correlation → Both relative importance percentages and directional relationships

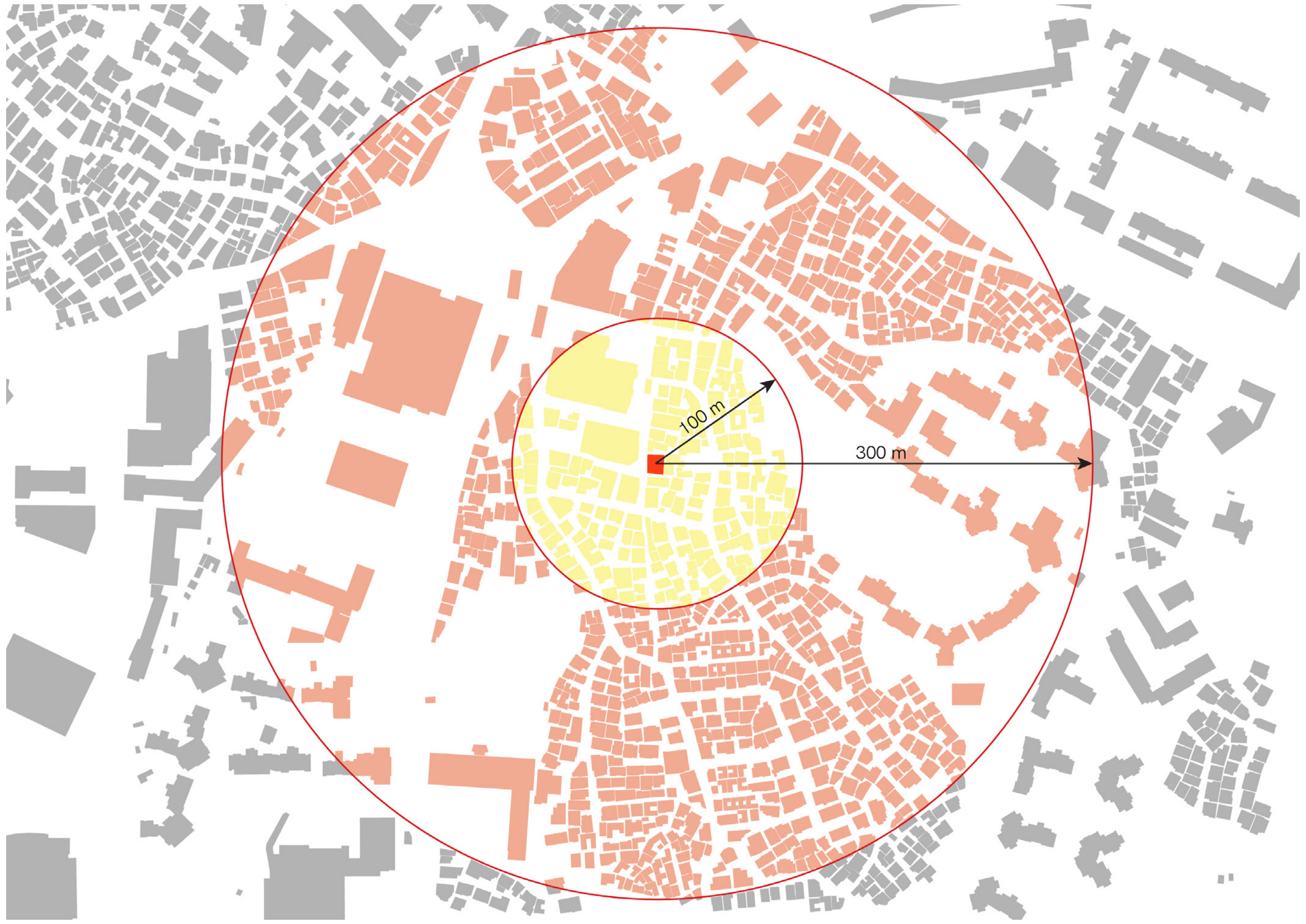
But no seasonal & scale-dependent analysis

Urban Form Element Important Analysis

Air Temperature Analysis



Energy Consumption Analysis



Pixel Scale **100m Buffer** **300m Buffer**

(Centroids of each pixel)

NDVI (Buffer)
Building Ratio (Buffer)
Building Volume (Buffer)
Weighted Height (Buffer)
GSI (Buffer)
FSI (Buffer)

100m Buffer **300m Buffer**

(Centroids of each building)

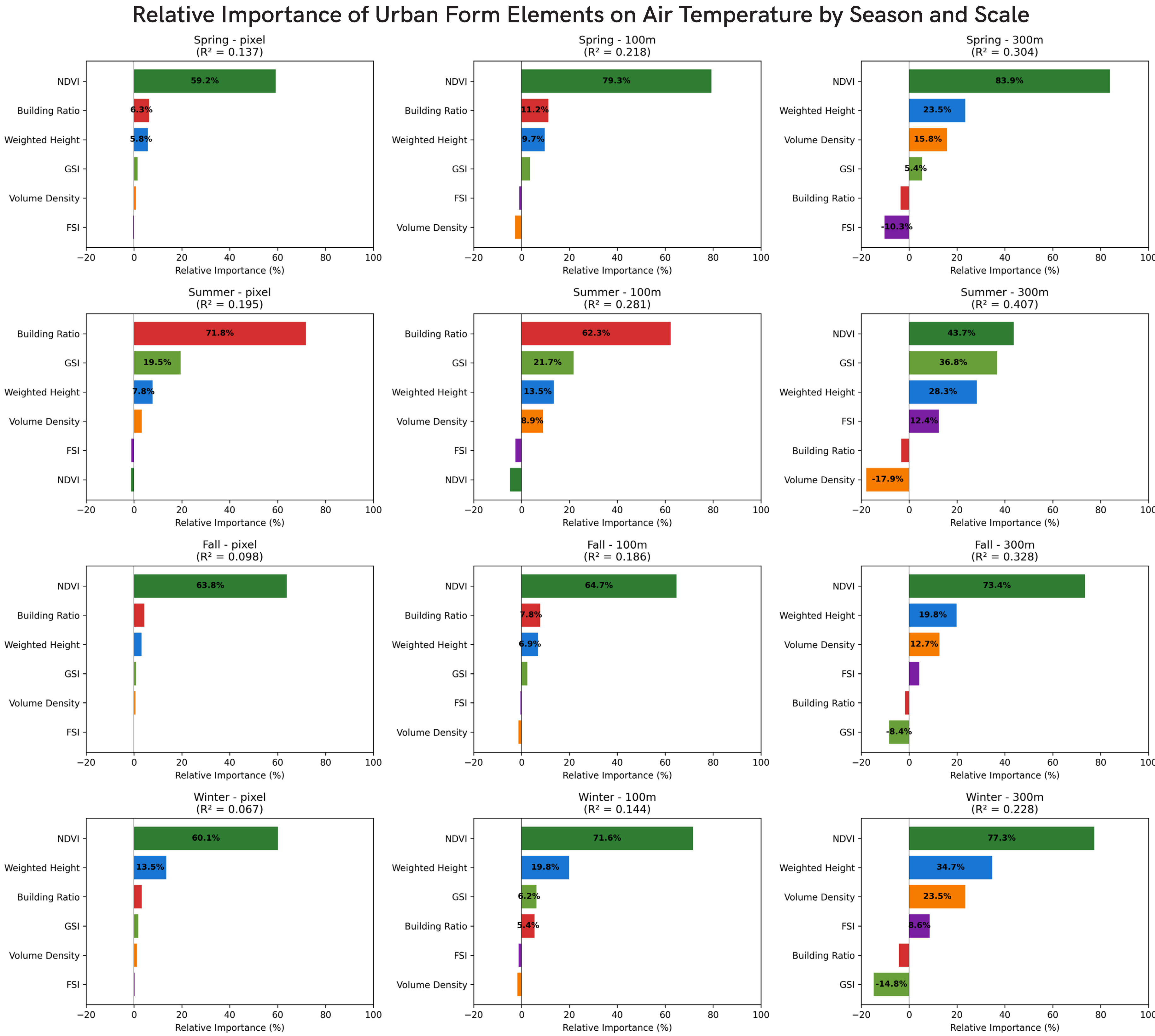
NDVI (Buffer)
Building Ratio (Buffer)
Building Volume (Actual)
Building Height (Actual)
GSI (Actual)
FSI (Actual)
Air Temperature (Buffer)

Air Temperature - Genizi Method

Scale	R^2
Pixel Scale	0.067 - 0.195
100m Buffer	0.144 - 0.281
300m Buffer	0.288 - 0.407

As scale gets bigger, higher predictive variance

Broader scales explain better air temperature variation



NDVI dominates in Spring, Fall, and Winter

Primary temperature changer throughout most of the year

Building characteristics become dominant in Summer (Builing Ratio & GSI)

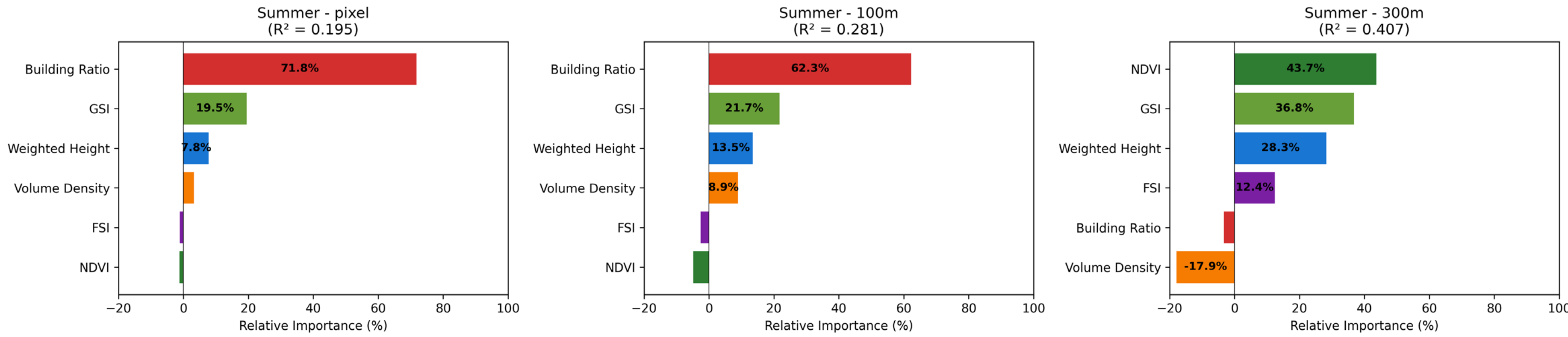
Physical presence and thermal mass of buildings overtake vegetation’s cooling effect

Air Temperature - Genizi Method

Significant Flip !

Builldng Ratio (Pixel)

NDVI (300m Scale)



Buildings get extremely hot as absorb heat

Vegetation areas stay low

→ Huge Difference

Pixel Scale

"Is there a building?"

Pixels with hot buildings create most of the temperature variation

300m Scale

Most buffers have similar proportions of buildings

(Building ratio does not tell much anymore)

"How much green space the area has?"

Scale	R^2
Pixel Scale	0.067 - 0.195
100m Buffer	0.144 - 0.281
300m Buffer	0.288 - 0.407

→ As scale gets bigger, higher predictive variance → Broader scales explain better air temperature variation

Electricity EUI - Genizi Method

Scale	**R^2**
100m Buffer	0.238 - 0.378
300m Buffer	0.152 - 0.262

↓

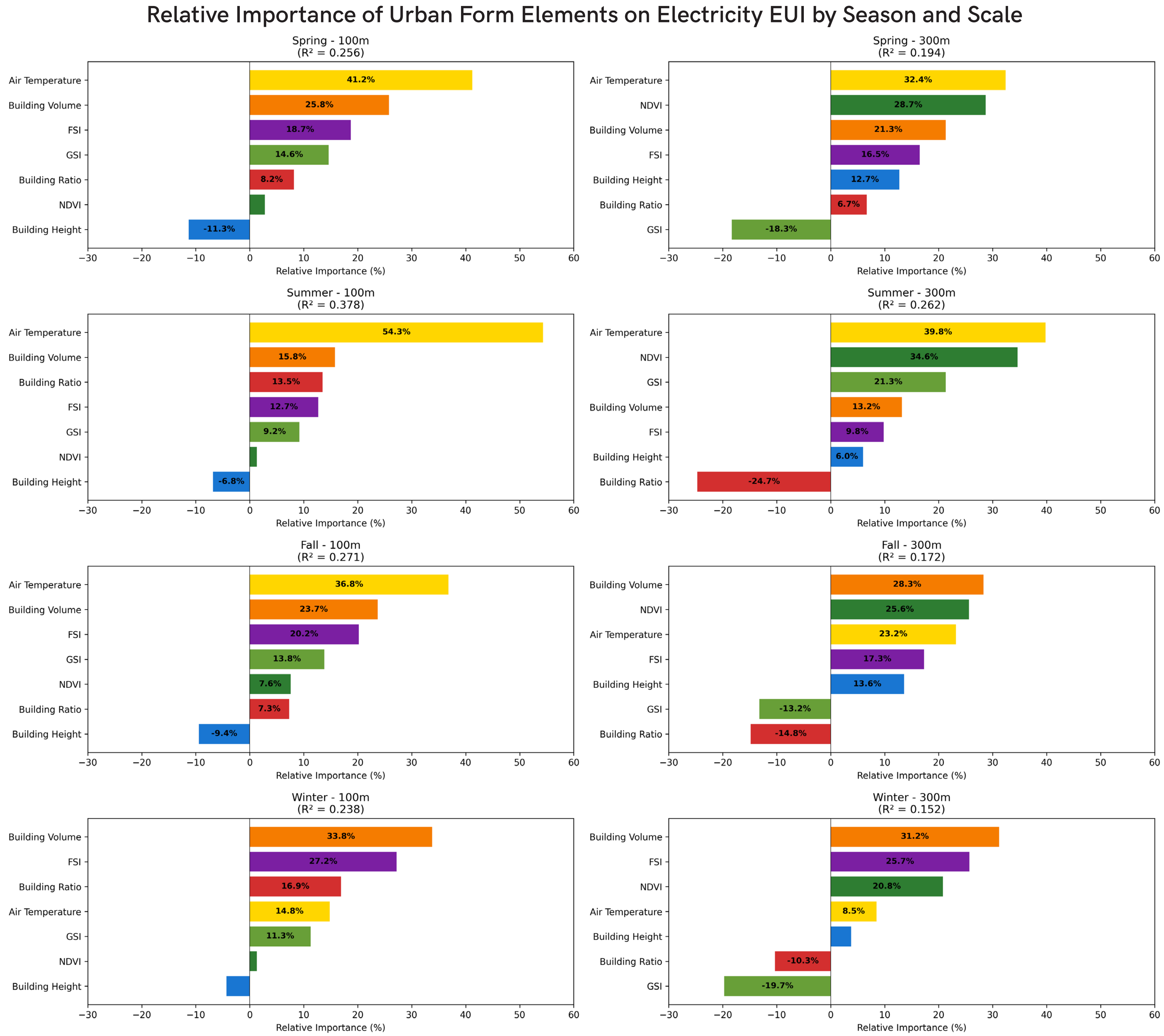
As scale gets bigger, lower predictive variance

↓

Smaller scale explains better electricity EUI pattern

Chen et al. (2019)   *Godoy-Shimizu et al. (2021)*

"finer resolutions better captured building-level variations"



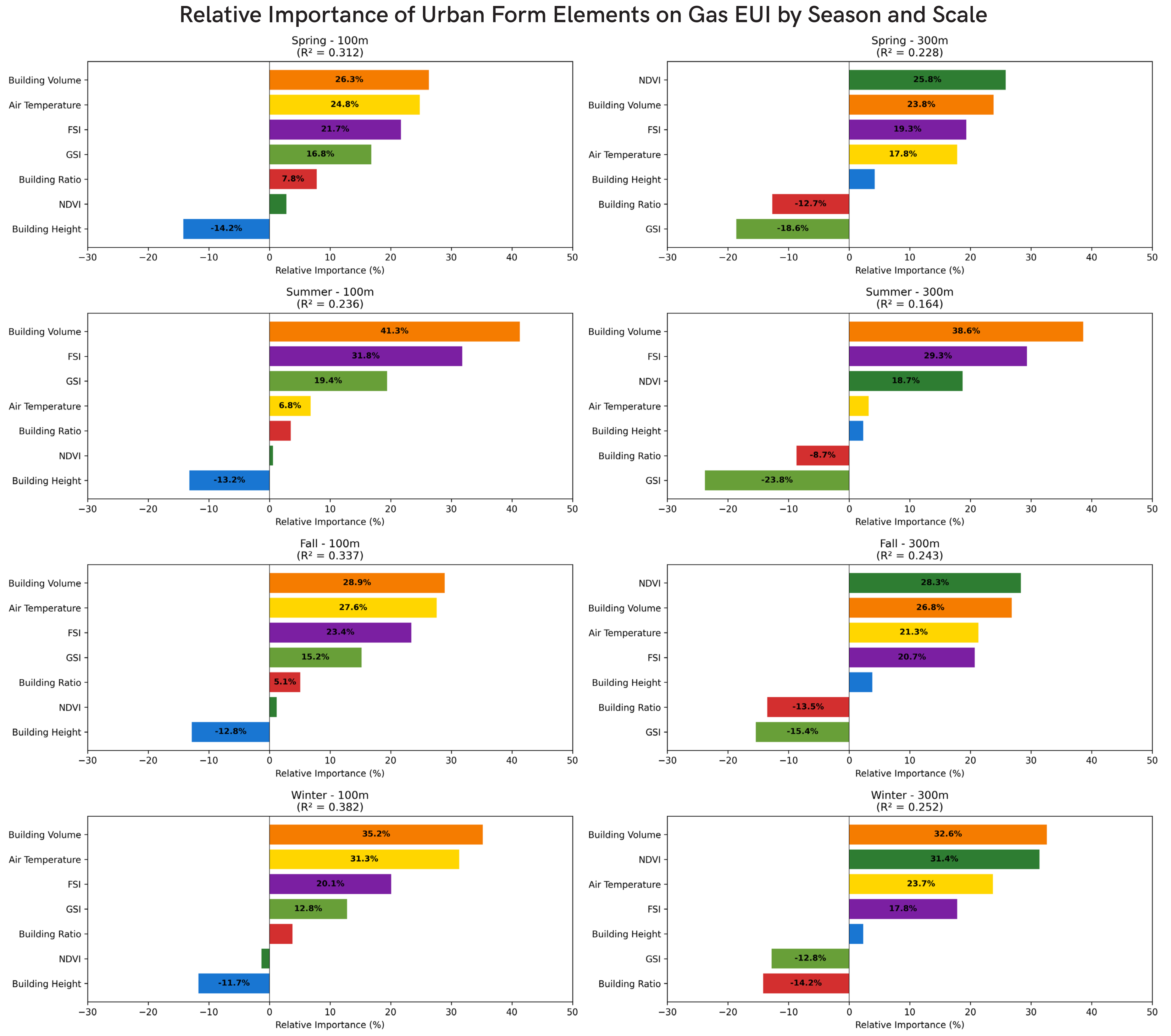
Air Temperature is the main driver in Summer

Electricity consumption is highly dependent on the Air Temperature

Building Volume is the second most important factor

Building size affect the electricity consumption (commercial vs residential)

Gas EUI - Genizi Method



Scale	R^2
100m Buffer	0.236 - 0.382
300m Buffer	0.164 - 0.252

As scale gets bigger, lower predictive variance

Smaller scale explains better gas EUI pattern

Building volume is the main driver across all seasons

Size of the buildings determines the gas use

Summer shows low R^2 and minimal temperature effect

Minimal heating demand and other factors drive summer gas use

Air Temperature - Partial Correlation

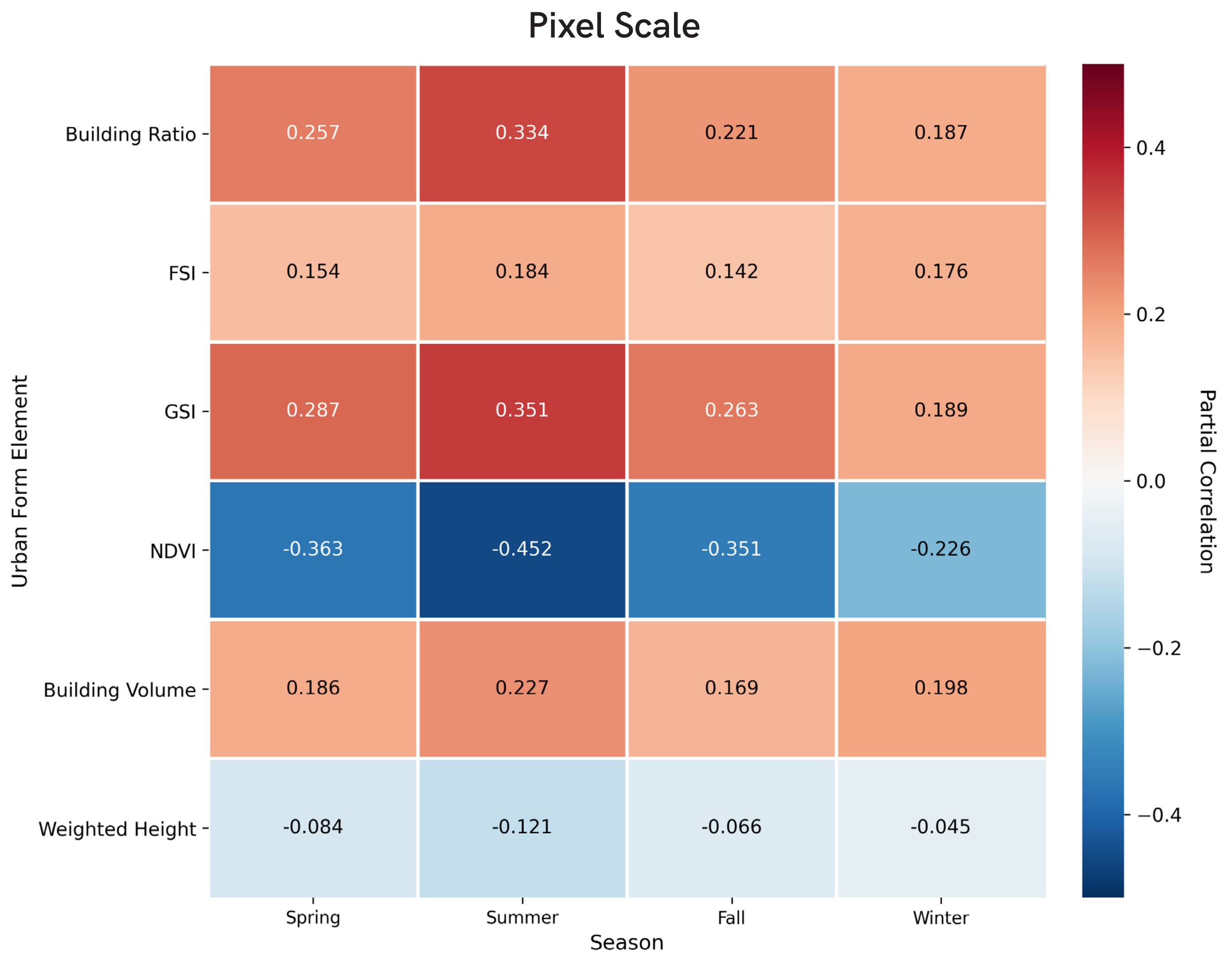
NDVI shows the strongest cooling effect in all seasons and scales

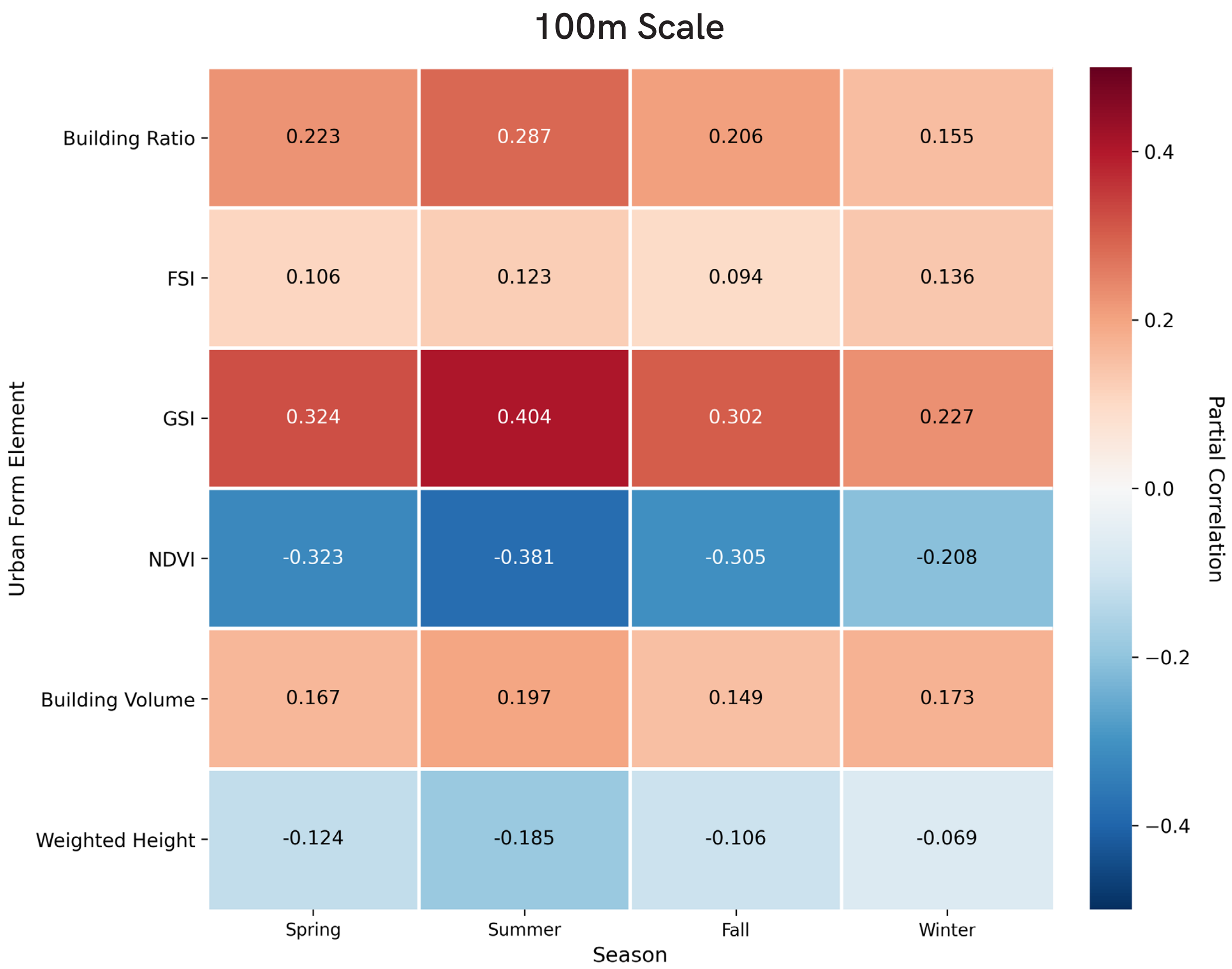
GSI & Building Ratio consistently show warming effects

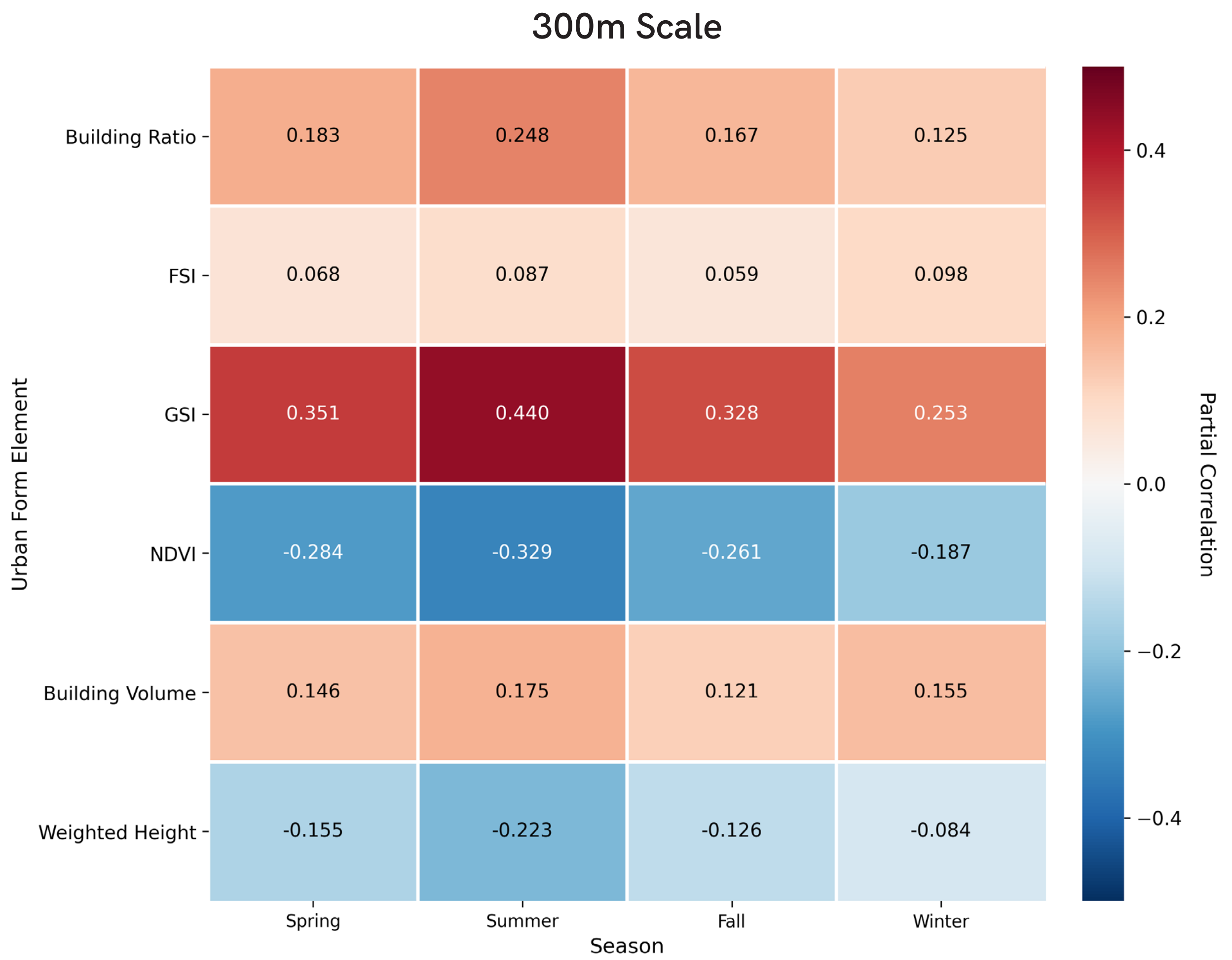
Weighted Height shows consistent cooling effects

NDVI's cooling effect (Pixel scale) & GSI's warming effect (300m scale)

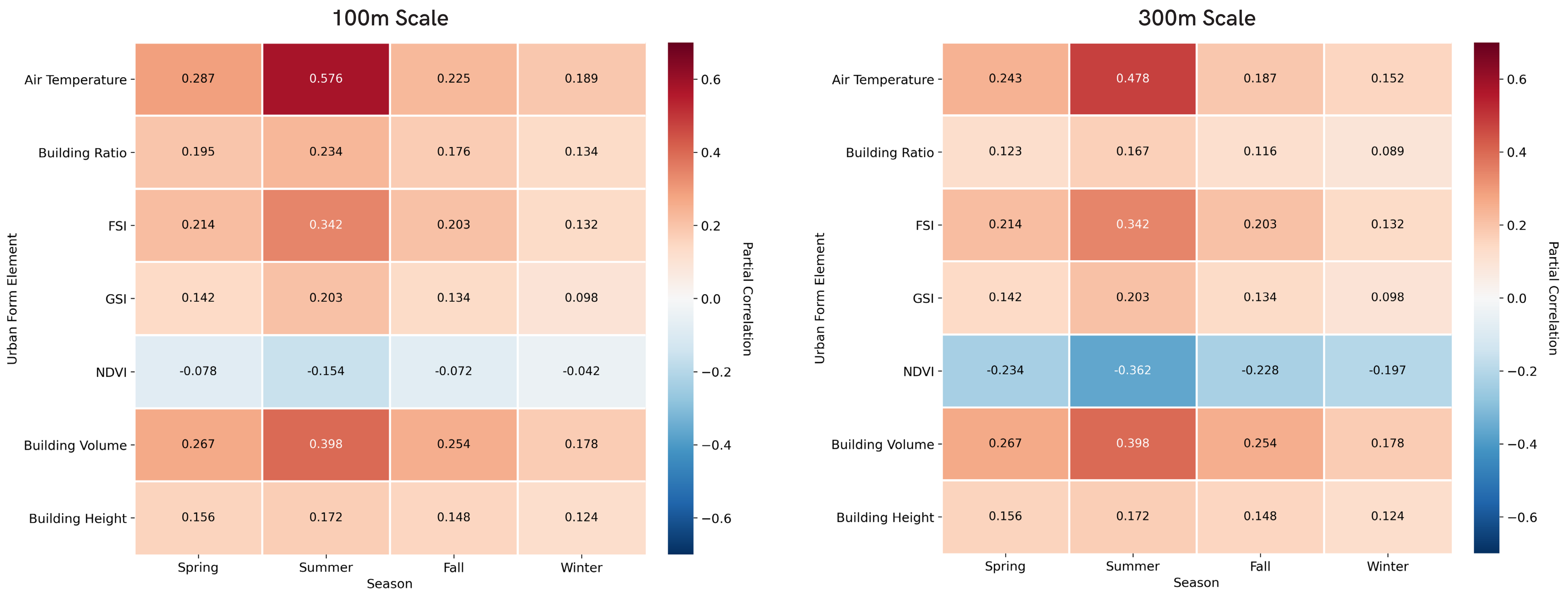
Vegetation (immediate scale) & Building related warming effects (neighborhoods)







Electricity EUI - Partial Correlation



Air Temperature is the dominant positive driver across all seasons

Cooling demands during hot weather due to air conditioning

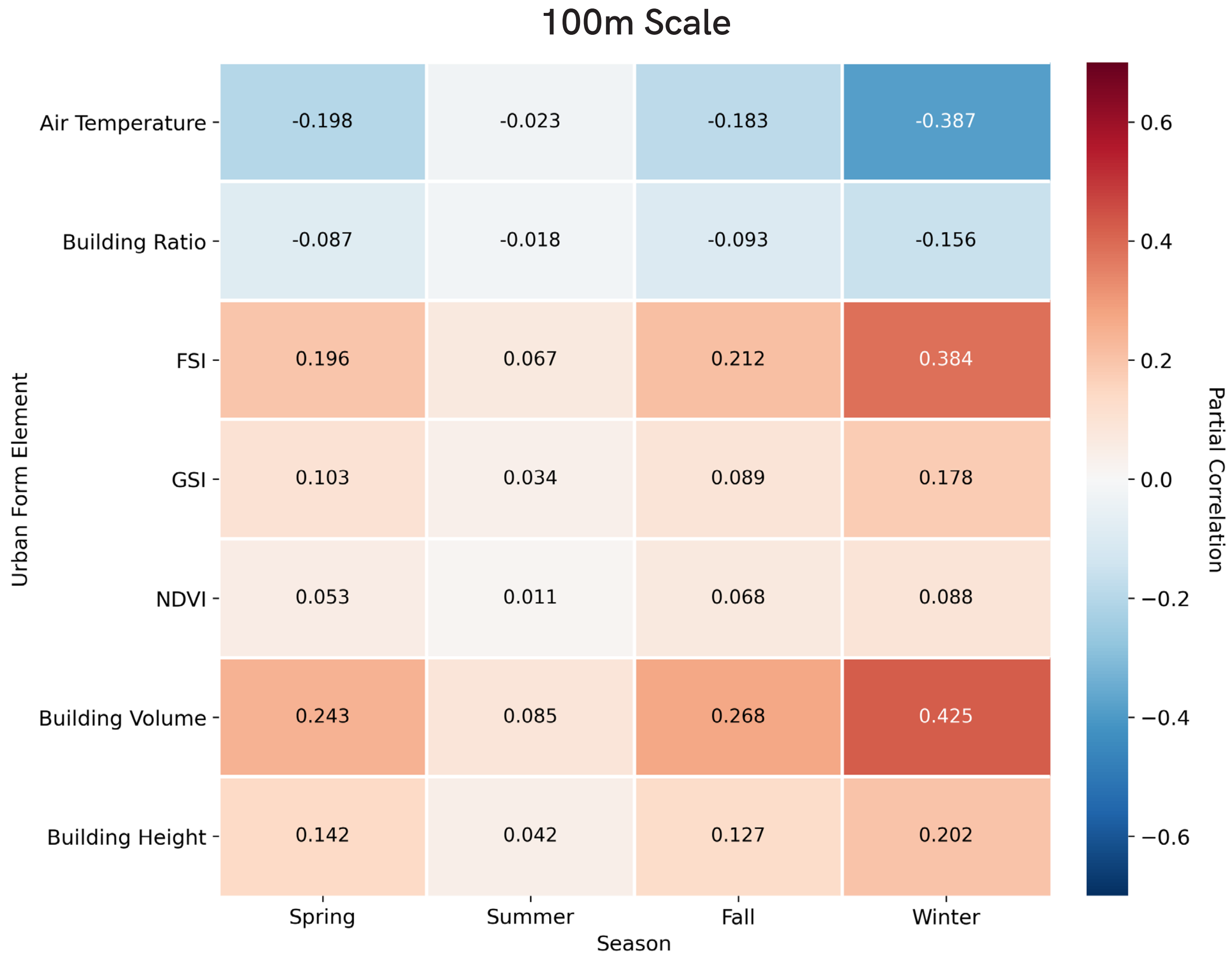
Building Volume shows the second strongest positive correlation

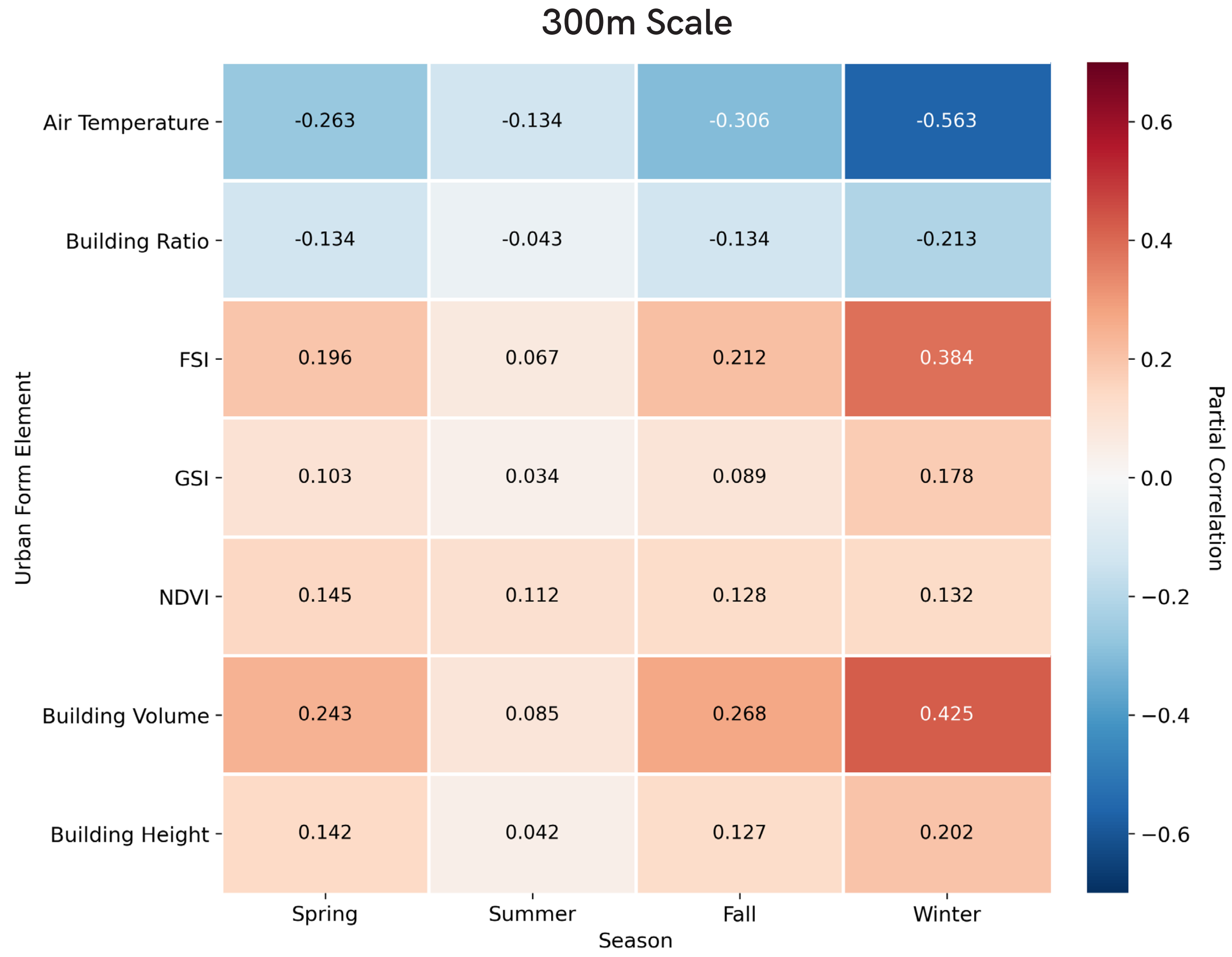
Big commercial buildings vs Small residential buildings

NDVI reduces electricity consumption due to cooling effect (especially in 300m)

Powerful cooling benefits in neighborhood-level vegetation

Gas EUI - Partial Correlation





Air Temperature has a negative directional relationship with gas consumption

Winter: people use more gas for heating

Building Volume shows the biggest positive factor and importance dramatically changes with seasons unlike electricity

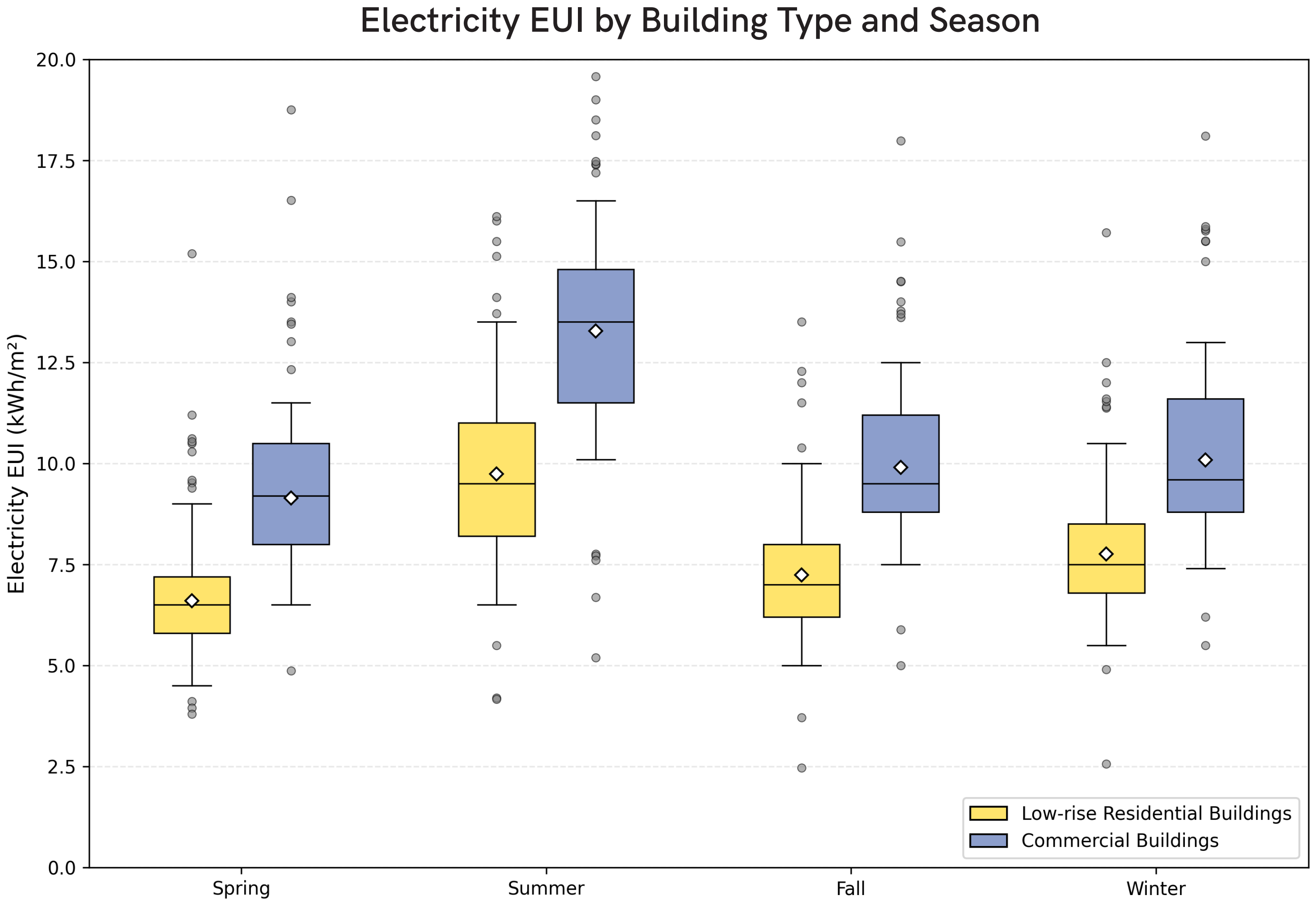
Gas = mainly used for heating

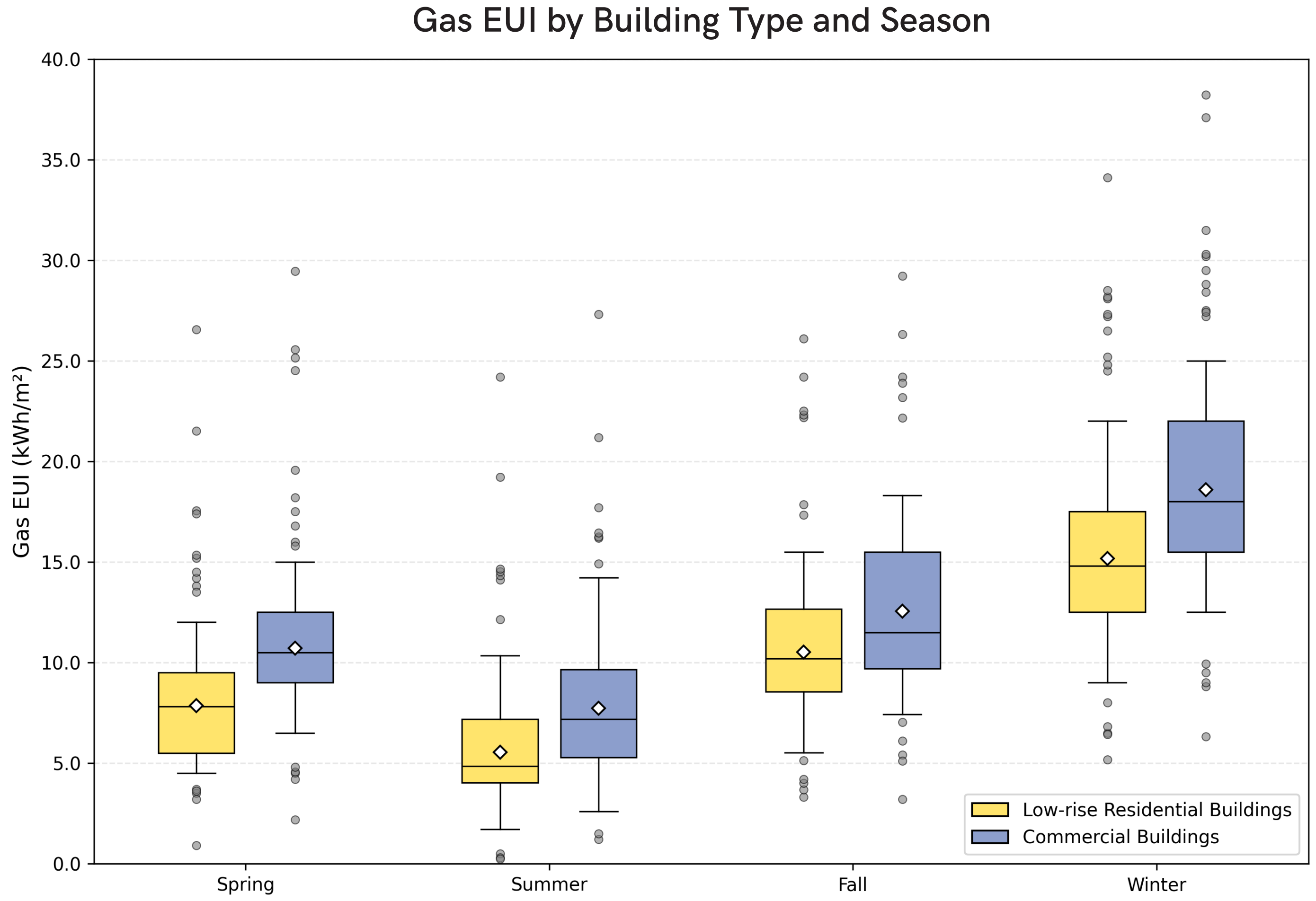
Electricity = used year-round for living appliances

Higher Building Ratio reduces gas consumption

Buildings packed together share walls and accumulate heat

Building Volume and Energy Consumption





	Electricity				Gas			
Mean EUI (kWh/m³)	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Low-rise Residential	6.60	9.74	7.24	7.76	7.86	5.54	10.52	15.16
Commercial	9.14	13.28	9.90	10.08	10.70	7.72	12.55	18.60
Difference	2.54	3.54	2.66	2.32	2.84	2.18	2.03	3.44

Average Building Volume — Low-rise residential Buildings (752.1 m³) < Commercial Buildings (7,123.9 m³)

Energy Use — Low-rise residential Buildings < Commercial Buildings (both Electricity & Gas)

Genizi Method + Partial Correlation

Air Temperature

As the scale increases, the prediction variance (R^2) increases

↓

Air Temperature is highly affected by neighborhood effects

Energy Consumption

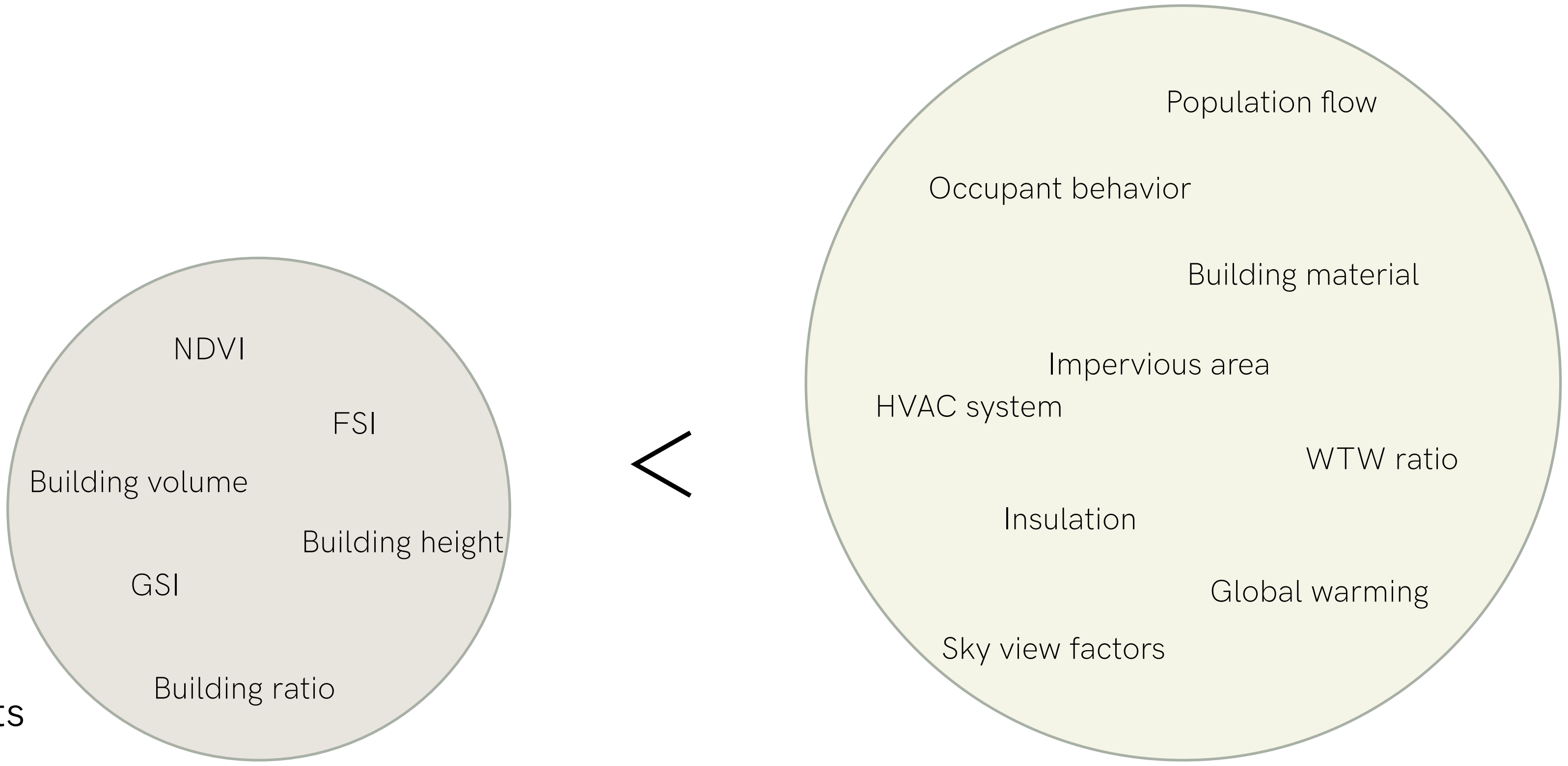
As the scale decreases, the prediction variance (R^2) increases

↓

Individual building characteristics matter more

NDVI shows a high cooling effect

Building volume highly affects energy consumption



~40% ~60%

The entire changing power is limited (unexplained UFE matter more)

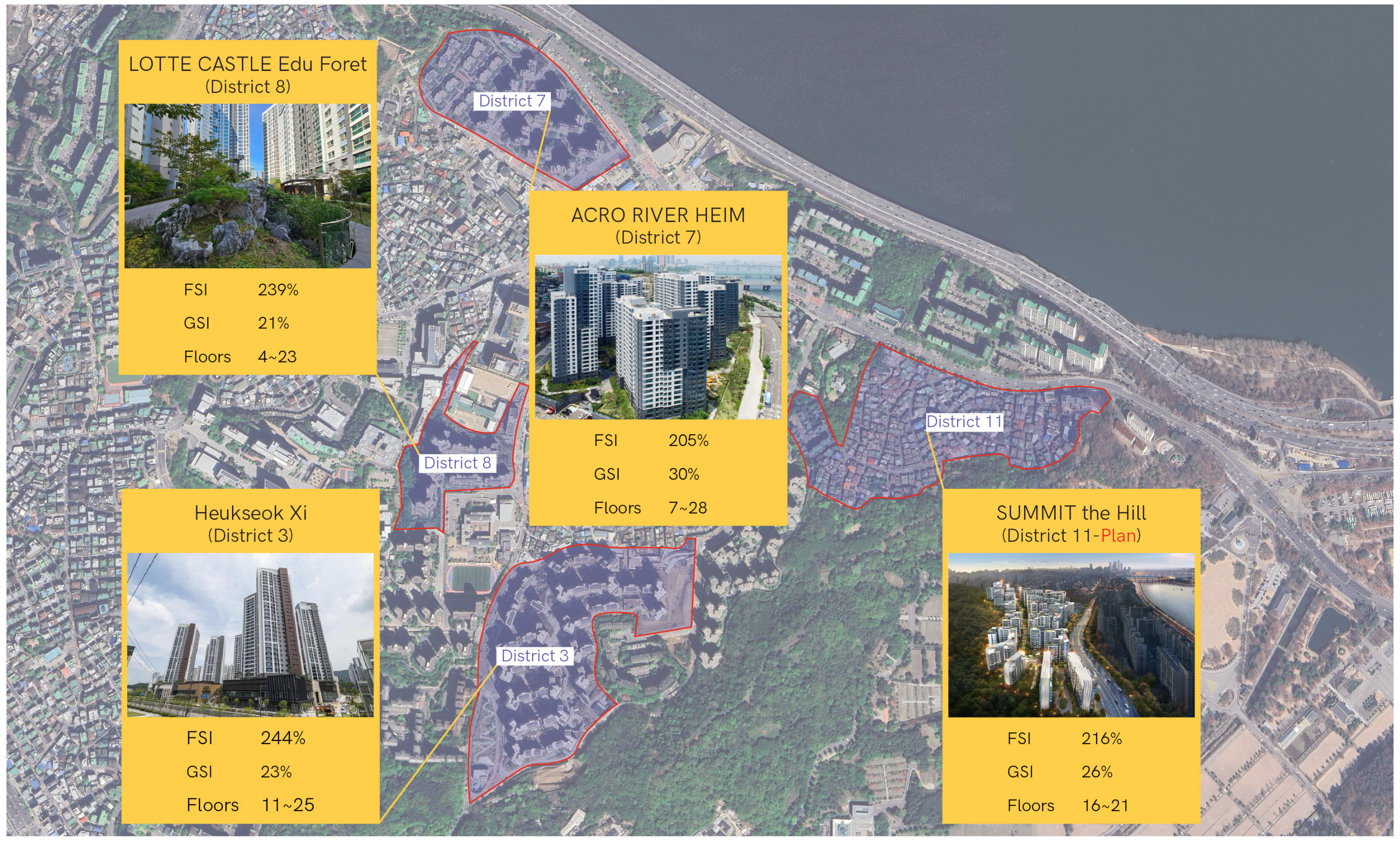
Changes over a Decade - Heukseok-dong

Satellite Picture of Heukseok-dong in Feburary 2015

3399 Buildings - 2015

Satellite Picture of Heukseok-dong in March 2024

2433 Buildings - 2024



Not happened in the entire Heukseok-dong

Only some districts have been transformed

Changes over a Decade - Heukseok-dong

Mean Air Temperature Change over a Decade in Heukseok-dong				
Year	Spring	Summer	Fall	Winter
2015	13.35 °C	23.80 °C	12.75 °C	-0.32 °C
2024	15.13 °C	26.78 °C	15.44 °C	-0.59 °C
Change	+13.1 %	+12.5 %	+21.1 %	-86.5%
Trend Line (per year)	+0.3156 °C	+0.2192 °C	+0.1712 °C	+0.0545 °C

Mean NDVI Change over a Decade in Heukseok-dong				
Year	Spring	Summer	Fall	Winter
2015	0.068	0.117	0.086	0.037
2024	0.089	0.131	0.108	0.042
Change	+30.3 %	+11.6 %	+25.8 %	+13.5 %
Trend Line (per year)	+0.00298	+0.00230	+0.00152	+0.000606

Urban Form Elements Change over a Decade in Heukseok-dong					
Year	Average Building Volume	Average Building Height	Average FSI	Average GSI	Average Building Ratio
2015	2,161 m^3	8.9 m	1.311	0.675	0.189
2024	3,116 m^3	9.3 m	1.384	0.550	0.167
Change	+44.2 %	+4.5 %	+5.6 %	-18.5 %	-15.7 %
Trend Line (per year)	+45.87 m^3	+0.0256 m	+0.004091	-0.00632	-0.00323

Average Building Volume has increased by 44.2 % (46 m^3 per year - Trend Line)

Increased NDVI and lower GSI

- Smaller footprints & mandated greening spaces

Air Temperature increased, even though increased NDVI and lowered GSI

- Increased NDVI and lowered GSI are not sufficient
- Other factors apart from 6 UFEs have stronger power to increase Air Temperature

Only redeveloped districts created most impacts

Changes over a Decade - District 3

Satellite Picture of District 3 in Feburary 2015

478 Buildings - 2015

Low-rise Resdiential Buildings

Satellite Picture of District 3 in March 2019

0 Buildings - 2019

Redevelopment Phase

Satellite Picture of District 3 in March 2024

28 Buildings - 2024

High-rise Apartments

Street View in District 3 in Feburary 2015

Street View in District 3 in March 2024

Changes over a Decade - District 3

Mean Air Temperature Change over a Decade in District 3

Year	Spring	Summer	Fall	Winter
2015	12.76 °C	23.15 °C	13.52 °C	-0.15 °C
2024	14.20 °C	24.31 °C	14.75 °C	-0.26 °C
Change	+11.3 %	+5.0 %	+9.1 %	-73.3 %
Trend Line (per year)	+0.1503 °C	+0.1632 °C	+0.1027 °C	+0.0353 °C

Mean NDVI Change over a Decade in District 3

Year	Spring	Summer	Fall	Winter
2015	0.051	0.104	0.074	0.025
2024	0.082	0.164	0.109	0.067
Change	+60.8 %	+57.7 %	+ 47.3 %	+168.0 %
Trend Line (per year)	+0.00353	+0.00450	+0.00219	+0.00253

Urban Form Elements Change over a Decade in District 3

Year	Average Building Volume	Average Building Height	Average FSI	Average GSI	Average Building Ratio
2015	1,175 m^3	10.0 m	1.331	0.705	0.263
2024	25,998 m^3	43.2 m	2.442	0.233	0.122
Change	+2,112.6 %	+332 %	+83.5 %	- 66.9%	-53.6 %
Trend Line (per year)	+2,456.63 m^3	+2.81 m	+0.3055	- 0.1088	-0.0514

Building Volume increased by 2,116% & Nearly doubled FSI

Less ground coverage and more green areas are created

Dramatically dropping GSI & Building Ratio, and a sigfinicantly higher NDVI

Air Temperature increased, even though increased NDVI and lowered GSI

Other factors apart from 6 UFEs have stronger power to increase Air Temperature

Compared to the entire Heukseok-dong, the temperature increases in District 3 is lower (12.5% vs 5.0% in Summer)

Reduced GSI and increased NDVI provided mitigation of temperature increases, despite a huge increase in Building Volume

Conclusion

Successfully converted LST to Air Temperature

Independent testing using S-DoT sensors confirmed systematic temperature difference (1.80°C vs 1.84°C)

Handled multicollinearity of using Genizi Method

Combining the Genizi Method with Partial Correlation

NDVI is the dominant cooling factor in most seasons, but **building characteristics** took dominance in Summer

Energy consumption patterns **smaller scale** & air temperature variations **broader scale**

6 UFEs explain only a portion of variance

Real-world validation of statstical finding (Increased NDVI & Decreased GSI, lower temperature increasing rate)

Empirical evidence from a long-term and **multi-scale analysis**

Discussion

Limitations of the Research

Energy consumption data were not available for all buildings in Heukseok-dong

Unexplained variance matter the most for energy consumption

Temporal limitations - Missing important diurnal temperature variations

- Single snapshot is representative of the entire month's temperature

Benefits of the Research

Sucessful conversion of satellite-based LST to Air Temperature

Long-term analysis & Seasonal Analysis

Cascade effects

Real-world redevelopment as validation

Thank you.

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Graduation Thesis

P5 Presentation

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