Reducing the Urban Heat Island Effect In Copenhagen

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A professional project submitted in
partial fulfillment of the
requirements for the degree of

Master of Urban Planning

University of Washington

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2013

Program Authorized to Offer Degree: Department of Urban Design and Planning

University of Washington
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The urban heat island effect is a well-known phenomenon that has been documented and studied in many urban areas. Put simply, an urban heat island effect occurs when a city is generally warmer than its surrounding hinterland, which tends to be less developed. Generally speaking, the urban heat island effect is the result of added solid surface horizontal and vertical geometry to a landscape that tends to trap solar radiation as heat. In 2010, an urban heat island effect was documented in Copenhagen, Denmark by researchers from the University of Copenhagen. The researchers also discovered that the urban heat island effect in Copenhagen was not uniformly distributed; that is, some streets and neighborhoods were hotter than others. The present study, undertaken as a professional project for the completion of the masters of urban planning degree from the University of Washington, attempts to explain what factors contribute to intra-urban temperature variation within Copenhagen. Climatic and urban form variables known to interact with urban heat island effect were identified and, to the extent possible given available data, were modeled in a GIS-based spatial statistics analysis. The modeling exercise returned results indicating a statistically significant relationship between the Normalized Difference Vegetation Index levels of a 150-meter buffer area surrounding the urban canyons and intra-urban air temperature variation amongst the canyons. The urban heat island effect presents a health concern within Copenhagen urban canyons during summer heat waves, when a population unaccustomed to high temperatures becomes susceptible to heat exhaustion and heat stroke with particular risk posed to the very young and old. As such, the present study evaluated the potential for green infrastructure elements to provide cooling to Copenhagen's commercial/residential urban canyons during the summer months. A literature search was conducted to evaluate the potential for green roofs, street trees, and urban parks to provide cooling available for horizontal transfer to urban canyons from a 150-meter buffer area

surrounding the canyons. Given that cooling is not desired in Copenhagen at any time of the year other than the summer months, cooling generated via evapotranspiration by vegetation inherent to green infrastructure is a logical solution as evapotranspiration peaks in intensity during the summer growing months. Although quantitative temperature reduction predictions could not be made, recommendations for more comprehensive modeling research are included herein along with a general discussion of design principles relevant to green infrastructure design interventions intended to provide cooling to urban canyons.

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Chair of the Supervisory Committee:

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INTRODUCTION

The Urban Heat Island effect has been of interest to climate scientists ever since Luke Howard found London to be warmer than its peripheral countryside in the early 19th century (Gedzelman et al. 29). Although the thermal conductivity and heat capacity of modern construction materials are not intrinsically higher than those of soils and flora, typical configurations of urban horizontal and vertical construction create a larger surface area for heat exchange than that typical of unbuilt, rural, or suburban areas. A significant amount of daytime solar energy is absorbed in the urban fabric by a relative abundance of vertical and horizontal surfaces and re-emitted as heat at nighttime (Oke 126). When combined with a heat wave, the urban heat island effect can pose serious health risks to urban communities. In locations where climate change is expected to increase temperatures, cities where an urban heat island effect exists may be at even greater risk. In the past decade, heat waves been responsible for thousands of deaths in cities across both Europe and North America. The threat of heatstroke is even a concern to citizens residing in the relatively northern city of Copenhagen.

The Danish Meteorological Institute reported 227 days with temperatures posing a slight risk of sunstroke/exhaustion and 37 days posing an increased risk of sunstroke/exhaustion between 1996 and 2009 (The Univsersity of Copenhagen 35). Sunstroke and exhaustion are known to be particularly dangerous in northern climates where the population is unaccustomed to hot temperatures, with particular danger posed to the elderly and sick (Swedish Commission on Climate and Vulnerability 29). As a result, the University of Copenhagen, in partnership with the Danish Hydraulic Institute and GRAS, a private satellite image processing and geographic information system (GIS) firm, produced an unpublished 2010 report in Danish entitled "Urban Heat Island in Copenhagen."

The researchers obtained Land Remote-Sensing Satellite (LANDSAT) surface temperature data for four 2006 days ("The University of Copenhagen" 23). GIS representation of the LANDSAT data (Figure 1) shows that surface temperatures within the Copenhagen postal districts were hotter than those of the surrounding land, which is characterized by a lesser-degree of urban development. A similar, normalized scale map displaying the difference between each individual data cell's surface temperature and the average surface temperature of the area surrounding each cell indicates that surface locations maintained analogous temperatures relative to other locations on each of the four days on which data was obtained (The University of Copenhagen 29). In other words, the hottest locations on one day were also the hottest locations on the other three observation days.

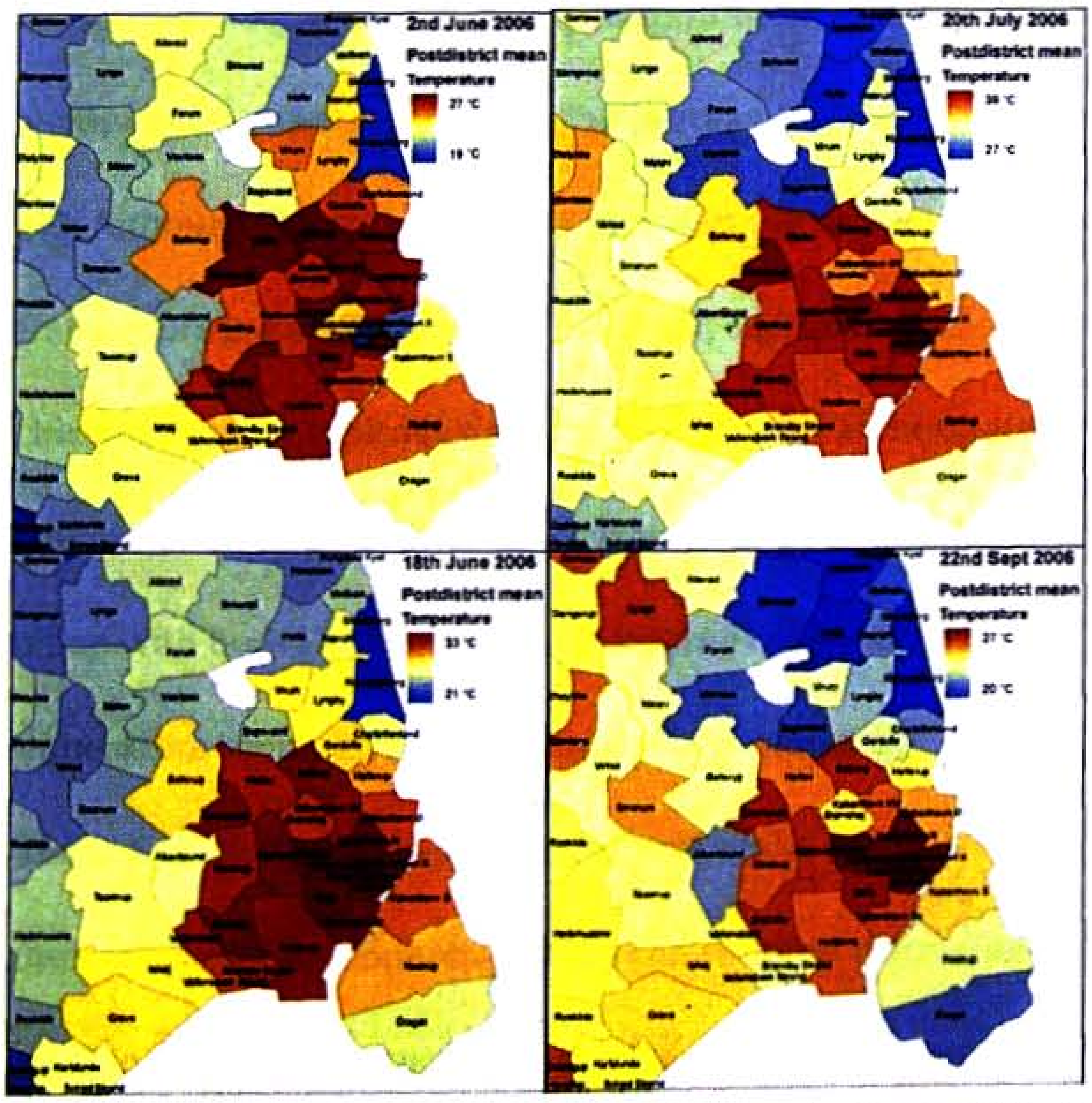


Figure 1: Average surface temperature by postal district ("The University of Copenhagen" 32)

As exemplified by Figure 1, none of the temperature maps included in the 2010 report display uniform temperature values within Copenhagen. To help explain intra-urban air temperature variation, the researchers tested the spatial correlation between Copenhagen surface temperatures and Normalized Difference Vegetation Index values for each of the four 2006 observation days. The Normalized Difference Vegetation Index is a dimensionless, remotely-sensed measure of near-infrared and red bands having a high correlation with vegetation leaf area index. Effectively, Normalized Difference Vegetation Index readings act as a surrogate measure for relative biomass (Jensen 382-386).

With simple linear regression analyses based on the overlay of surface temperature and Normalized Difference Vegetation Index GIS data, the researchers were able to show statistically significant spatial relationships between 60-meter by 60-meter surface temperature data cells and 30-meter by 30-meter Normalized Difference Vegetation Index value data cells for each of the four 2006 observation days. The average R square value for the four regression models was .440. Although Figure 1 displays a summertime urban heat island effect based on surface temperature measurements, both human comfort indices and temperature reduction achievements are typically described in terms of air temperature. As such, the researchers compared air temperature data collected at the Danish Meteorological Institute's monitoring station with both LANDSAT and Moderate-Resolution Imaging Spectroradiometer surface temperature readings, finding a linear relationship between air and surface temperature data ("The University of Copenhagen" 25). Effectively, it can be said that 44% of changes in air temperature within Copenhagen are the result of Normalized Difference Vegetation Index level variation. The study naturally concluded that a higher proportion of vegetation at any given location within Copenhagen results in a lower air temperature at that location ("The University of Copenhagen" 38). The 2010 report acknowledges other variables, in addition to Normalized

Difference Vegetation Index, that are likely to affect intra-urban air temperature variation. These include anthropogenic heat, wind, thermal admittance, building mass, and building geometry ("The University of Copenhagen" 12). In the following sections, an attempt to model a selection of the variables potentially affecting Copenhagen's intra-urban temperature variation is described.

An attempt to model the effect of a selection of variables affecting Copenhagen's intra-urban temperature variation was made to inform the early stages of a University of Copenhagen effort to create a climate change adaptation plan for the city in collaboration with the Copenhagen Municipality's Center for Parks and Nature. The 2010 University of Copenhagen report had demonstrated that 44% of intra-urban air temperature variation amongst 60-meter by 60-meter surface temperature data cells could be explained by changing levels of the Normalized Difference Vegetation Index value amongst 30-meter by 30-meter data cells. The University of Copenhagen was, in effect, interested in exploring how vegetation might be added to its residential and commercial urban canyons to reduce temperatures where people are likely to be adversely affected by heat waves. To this aim, I was asked to research to what degree green infrastructure elements might be able to strategically reduce urban canyon air temperatures. If I was unable to predict quantitative reductions, I would describe how the University of Copenhagen could attain predictive information.

Prior to researching the potential for green infrastructure to reduce Copenhagen's urban heat island effect, I was asked to model additional climatic and urban form variables understood to theoretically affect intra-urban temperature variation. This modeling exercise was intended to explore other potential causal relationships accounting for the remaining share (approximately 56%) of Copenhagen's intra-urban air temperature variation. In addition, I modeled the Normalized Difference Vegetation Index variable at a different scale using a more familiar urban fabric unit – the urban canyon – as the spatial data aggregation unit. Theoretically, a better understanding of how variables affect temperature variation would provide insight into how urban design interventions might be selectively made to reduce the urban heat island effect in Copenhagen, particularly in the areas presenting the greatest health risks during summer heat waves.

This document describes the process I undertook to respond to the research and modeling requests made of me by the University of Copenhagen in order to fulfill the thesis/professional project required for completion of the Masters in Urban Planning degree from the University of Washington. I began by conducting a targeted literature analysis, described in the next section. The purpose of the literature analysis was to try to understand how climatic and urban form characteristics can be spatially modeled using a GIS platform with urban canyons used as the spatial data aggregation unit. Following the literature analysis, my spatial statistics modeling method is described in detail. Next, in light of the results of the modeling method, a discussion of the potential for green infrastructure to strategically reduce the urban heat island effect in Copenhagen urban canyons is included along with a description of other modeling options. Finally, a description of the communication methods I used to deliver my findings to the University of Copenhagen and the Copenhagen Municipality's Center for Parks and Nature is included followed by a conclusion section.

LITERATURE ANALYSIS

The University of Copenhagen 2010 report identified climatic and urban form variables that affect intra-urban temperature variation. Before selecting any of these variables for modeling in isolation or in combination with one another, the theoretical grounds on which each variable is considered to interact with urban air temperature variation was researched. Studies in climatology journals were consulted that described the climatic and urban form variables considered to affect intra-urban temperature variation. Once an understanding of intra-urban temperature variation was gained, variables were selected to model based on the availability of spatial data. Other climatology studies were also consulted that describe how the identified variables have been previously modeled using numeric computer models, hardware scale models, and empirical observation methods.

To comprehensively understand the variables known to affect intra-urban temperature variation, the early theoretical work of Tom Oke, professor emeritus from the University of British Columbia's Geography Department, can be consulted. Oke developed the urban surface energy balance equation, which describes energy inputs to the built environment in relation to how energy fluxes are distributed as heat at the surface of the built environment. Importantly, built environment microclimate and urban form elements have subsequently been identified associated with variables on both sides of the urban surface energy balance equation (see Table 1). Oke described the urban Surface energy balance framework in 1988 as $Q^* + Q_F = Q_H + Q_E + Q_S + \Delta Q_A$ (Pigeon et al. 1971).

Urban Surface Energy Balance Variables	Equation Symbol	Examples of Associated Microclimate and Urban Form Elements
New All Wave Radiation	Q^*	Albedo
New All Wave Radiation	Q^*	Pollution
New All Wave Radiation	Q^*	Cloud Cover
New All Wave Radiation	Q^*	Urban Canyon Openness
Anthropogenic Heat	Q_F	Traffic
Anthropogenic Heat	Q_F	Building Interior Heating
Anthropogenic Heat	Q_F	Industrial Waste Heat
Turbulent Sensible Heat Flux	Q_H	Air Temperature
Turbulent Latent Heat Flux	Q_E	Normalized Difference Vegetation Index
Net Storage Heat Flux	Q_S	Building Mass
Net Horizontal Advective Heat Flux	ΔQ_A	Wind

Table 1: Urban surface energy balance

Net all wave radiation (Q*)

Net all wave radiation (Q*) represents the net sum of solar radiation, both shortwave and longwave, available for distribution to energy fluxes at the urban surface. The amount of available shortwave radiation is dependent upon latitude, cloud cover, pollution levels, and the albedo of surface materials (Grimmond 108). Clouds, air pollutants, and surfaces with a positive reflection coefficient immediately return a percentage of short wave radiation back to the atmosphere. Shortwave radiation not reflected is absorbed by surface materials and subsequently re-emitted as longwave radiation (Arnfield 8).

At the block scale, variety in the albedo and geometry of the urban surface affects how much solar radiation will be made available for energy exchange to other energy flux variables. Surfaces with higher reflection coefficients will return more incoming shortwave radiation to the atmosphere. As such, it is often suggested that existing materials with low reflection coefficients be replaced in order to reduce a local urban heat island effect. In the case of Copenhagen and other northern climate cities where the urban heat island effect is only problematic during summer heat waves, however, permanent changes to surface albedos are not desirable as they would also create unwanted winter cooling.

Before developing the urban surface energy balance formula, Oke had conducted a number of research studies related to the way built environment surface characteristics interact with longwave radiation. In 1981, he constructed a hardware scale model mimicking a prototypical city composed of urban canyons. Urban canyons are individual city streets flanked by buildings and side street gaps. The model showed that under clear sky and calm air conditions with no anthropogenic heat contribution, the relative openness of an urban canyon affected the local rate of cooling with a maximum urban heat island effect of eight degrees Celsius (Arnfield 17; Chapman, Thornes, and Bradley 81). In principle, when an urban canyon is less open, it should cool less efficiently as re-emitted longwave radiation becomes trapped in the canyon by multiple reflections off of vertical canyon walls. Shortwave radiation that enters a tall, narrow canyon during the day will be trapped to a higher degree than in a short, wide canyon. A taller, narrower canyon will permit less solar radiation from entering the canyon; however, Oke modeled a prototypical city without tall, narrow canyons.

Urban climatologists have sought to corroborate Oke's scale model findings in many different geographies using numerical modeling and empirical observation (or some combination thereof). In 2004, Unger summarized 14 studies that had examined the relationship between urban canyon openness and intra-urban temperature variation. Out of 39 total cases from the 14 studies, 23 reported a significant relationship, showing that urban canyon temperatures decrease with canyon openness (255-257). In Scandinavia, a significant relationship between canyon openness and surface temperature was found in both Malmö and Gothenburg (Barring, Mattson, and Lindquist 333-444; Eliasson et al. 1-16).

When investigating the connection between intra-urban temperature variation and urban canyon openness, researchers select from two metrics to quantify urban canyon openness: 1) the height-to-width ratio of the canyon or 2) the urban canyon's sky view factor.

The sky view factor is a dimensionless measure of the average view factor from the base of an urban canyon to the sky (Ratti, Di Sabatino, and Britter 81). To measure the sky view factor, a picture is taken from within an urban canyon looking upwards with a fisheye lens. This image is digitally or manually quantified on a scale from zero to one such that canyons with a greater presence of buildings and trees obscuring the image are assigned a higher value. Lindberg was critical of the common sky view factor method, reporting that in Gothenburg the sky view factor areal mean correlated more strongly with intra-urban temperature variation than when only one fisheye image per urban canyon was input into the model (Lindberg 264). Furthermore, variations in image conditions have made it difficult to develop an objective algorithm for quantifying the sky view factor across studies (Chapman, Thornes, and Bradley 82). Some researchers have effectively begun to calculate sky view factor values using a GIS with digital elevation models and a consistent shadow-casting algorithm (Lindberg 264). Ratti and Richens as well as Chen et al. have advocated for this raster-based digital elevation model approach (Ratti and Richens 297-309; Chen et al. 121-136). The digital elevation model approach relies solely on ground and building topography, thereby ignoring vegetation that may trap re-emitted longwave radiation (Lindberg 265).

The height-to-width ratio is the ratio of the mean height of the canyon buildings and side street gaps to the mean width of the canyon street including sidewalks (Lindberg 263). The height-to-width metric is typically calculated with city GIS data that includes spatial attributes defining the width of streets and building dimensions. Like the digital elevation model approach to calculating an urban canyon's sky view factor, the height-to-width ratio metric does not account for the presence of trees that may, like buildings, trap outgoing longwave radiation.

Anthropogenic Heat (Q_F):

The second source of energy accounted for by the urban surface energy balance equation is that which is produced by human activity. Significant anthropogenic heat may derive from transportation, lighting, appliances within buildings, heating, air conditioning, and industry. For European cities, anthropogenic heat within a range of 5-35 W m^{-2} has been reported with seasonal, weekly, and diurnal variation (Hove et al. 10). In the winter months, for instance, households are more likely to use heating sources, especially during days and hours when they are at home.

Several attempts to model contributors to anthropogenic heat with respect to intra-urban temperature variation have been made. To model interior heating and cooling sources, for example, inventories of energy consumption have been spatially correlated with temperature at the mesoscale (Pigeon et al. 1969-1981). In Gothenburg, however, Lindberg found no significant spatial correlation between district heating and temperature (269). Given that buildings in Copenhagen (like those in Gothenburg) tend to be highly insulated, an investigation into the contribution of anthropogenic hear from cooling and appliance sources from within residential and office buildings would be unlikely to contribute significant results.

Based on remote sensing images included in the 2010 University of Copenhagen report, industrial sources of heat do appear to contribute to intra-urban temperature variation and the urban heat island effect. The report concludes that Vesterbro was the hottest city district in the summer of 2006 and images of surface temperatures in Vesterbro on July 20th, 2006 show that several areas stand out as being hotter than others ("The University of Copenhagen" 32). A bicycle trip I made through Vesterbro with surface temperature maps from the 2010 report revealed that the Carlsberg brewery, DSB repair station, and the H.C. Ørsted Power Station were amongst the hottest locations. To what degree the relatively high surface temperature at these sites is due to the release of industrial waste heat would require on-site empirical data collection. Additional research inquiries might investigate how Vesterbro industrial waste heat is spread by wind to adjacent areas.

Turbulent Sensible Heat Flux (Q_H):

The turbulent sensible heat flux, synonymous with the heating of air, is driven by net availability of energy input by anthropogenic heat and longwave/shortwave radiation. In one sense, the turbulent sensible heat flux represents a residual vector in that energy not diverted to the latent sensible heat flux or the net storage heat flux becomes available for the sensible heat flux. The turbulent sensible heat flux can be directly measured with empirical observation tools as simple as air thermometers. The turbulent sensible heat flux for Copenhagen was indirectly measured by researchers contributing to the 2010 University of Copenhagen report when they determined a linear relationship between Copenhagen surface temperatures and air temperature. As such, following conversion from Kelvin scale surface temperature data, turbulent sensible heat flux GIS data specific to Copenhagen was available for inclusion in my modeling of variables affecting Copenhagen's intra-urban temperature variation.

Turbulent Latent Heat Flux (Q_E):

The size of the turbulent latent heat flux, which is closely associated with evaporation, is dependent upon the presence of both vegetation and moisture at the urban surface. Energy absorbed into the turbulent latent heat flux is expended by the process of evaporation, effectively cooling nearby surfaces and ambient air while diverting energy from the turbulent sensible heat flux. On the urban surface, the availability of water is influenced by precipitation events and the degree to which precipitation is retained or drained away at the surface. In addition to the evaporation that occurs on sealed surfaces, vegetation, via the process of evapotranspiration, evaporates water (Grimmond 111).

The air temperature cooling potential of evaporation has been modeled at the city, neighborhood, and block scales using hardware scale models, numerical modeling, and empirical observation. Particular attention has been paid to the cooling benefits of existing city parks. The cooling potential for other forms of green infrastructure, such as street trees and green roofs, has also been investigated with numerical and hardware scale modeling. Given vegetation's significant role in contributing to urban surface evapotranspiration, Copenhagen's turbulent latent heat flux can be partially modeled using Normalized Difference Vegetation Index GIS data.

Net Storage Heat Flux (Q_S):

The net storage heat flux represents the net uptake and release of energy by buildings, vegetation, and ground surfaces. The ability of materials to store and release heat is known as thermal admittance, which is the product of thermal conductivity and heat capacity (Grimmond 112-113). Although most researchers assume that aggregate heat capacities and thermal admittance levels are generally higher in cities than in rural areas, no strong evidence has yet to be presented to verify this assumption (Hove et al. 31). According to Grimmond, the size of the net storage flux is dependent upon surface materials, morphology, and thermal mass (113). Arnfield went so far as to say, however, that modeling the net storage heat flux with a representative sample of urban facets like surface materials and thermal mass would not be possible (Arnfield 7).

Net Horizontal Advective Heat Flux (ΔQ_A):

The net horizontal advective heat flux represents the flow of energy between fluxes as a result of horizontal and vertical changes in surface characteristics. Variation in surface temperatures, moisture, and surface roughness generate a spatial gradient driving the flux. On the mesoscale, for example, the presence of a city next to a body of water will result in a sizeable net horizontal advective heat flux in the form of a sea breeze. On the microscale, well-irrigated grass next to a road will result in measurable advection resulting from a steep moisture gradient (Grimmond 113). For simplicity purposes, advective forces are categorically referred to as "wind" herein.

Generally speaking, wind speeds are lower in cities in comparison to their surroundings, though increased turbulence and wind speeds are common within urban canyons (Lindberg 269). Increased turbulence results from larger surface roughness produced by non-uniform building geometry. Employing hardware scale models with simplified building layouts of uniform urban canyons arranged as parallel slabs, urban wind regimes can be predicted based on the height-to-width and length-to-width ratios of the canyons (Lindberg 269). Given that actual urban geometries are never simplified, the urban heat island effect is generally modeled without considering wind (Gedzelman 29).

METHODS

Based on a literature analysis of research related to the urban surface energy balance using Oke's 1988 equation as an organizing principle, a selection of microclimatic and urban form element variables can be made to model intra-urban air temperature variation. In the GIS-based spatial statistics model, air temperature was the dependent variable and a selection of microclimatic and urban form variables were the independent variables. The purpose of the model was to investigate to what degree selected microclimatic and/or urban form variables affect intra-urban air temperature variation amongst Copenhagen urban canyons. If statistically significant results were found, then this information would potentially be used to inform design intervention decisions with the intent to reduce summertime air temperatures within urban canyons. In other words, design interventions could be tailored to counteract the microclimatic and/or urban form conditions that most correlate with Copenhagen urban canyon air temperature variation. As mentioned, the availability of data influenced the selection, summarized in Table 2.

Examples of Associated Microclimate and Urban Form Elements	Selection for Modeling	Reason for Omission
Albedo	No	Irrelevance
Pollution	No	Scale
Cloud Cover	No	Scale
Urban Canyon Openness	Yes	N/A
Traffic	No	Data Availability
Building Interior Heating	No	Irrelevance
Industrial Waste Heat	No	Data Availability
Air Temperature	Yes	N/A
Normalized Difference Vegetation Index	Yes	N/A
Building Mass	No	Irrelevance
Wind	No	Data Availability

Table 2: Selection of urban surface energy balance variables

Selected Variables

The selected variables were air temperature, the Normalized Difference Vegetation Index, and urban canyon openness. These variables were selected on the basis of data availability and relevance to intra-urban air temperature variation. Air temperature was selected as the dependent variable as it is more relevant to human health and comfort during summer heat waves than surface temperature. The Normalized Difference Vegetation Index was selected to represent the turbulent latent flux. Urban canyon openness was selected to represent, as much as possible, net all wave radiation. Further description of the selected variables is given below.

Omitted Variables

Albedo, building interior heating, and building mass were each excluded from the selection on the basis of irrelevance. Although changing the albedo of surface materials in Copenhagen might very well reduce the amount of incoming shortwave radiation to the urban surface by, for example, painting rooftops white, the effect would be to reduce surface and air temperatures year-round. The urban heat island effect in Copenhagen, in contrast, is a seasonal problem and lower temperatures during the non-summer months are not desirable.

The heat produced within buildings has shown to be a significant source of exterior urban heat by several studies (Pigeon et al. 1969-1981). It is unlikely, however, that buildings in Copenhagen emit significant amounts of heat due to high standards of insulation intended to reduce heat loss in the winter months. Furthermore, a study in a comparable Swedish city did not show a significant relationship between interior building heat and intra-urban temperature variation (Lindberg 269). Industrial areas were shown by the 2010 University of Copenhagen study to generate measurable amounts of waste heat, particularly in the Vesterbro neighborhood. As mentioned, empirical observation methods could be used to register both the amount of waste heat produced by industrial sites and the vectors by which this heat is spread to nearby urban canyons. As of 2013, this data is not known to be available. The exclusion of building mass Is based on Arnfield's assertion that modeling the net storage heat flux accurately would not be possible with known data collection and analysis methods (Arnfield 7).

Pollution and cloud cover were omitted from the variable selection on the basis of scale. Pollution levels and clouds are known to reduce the amount of incoming shortwave radiation to the built environment surface at the city-wide or mesoscale by virtue of reflection (Arnfield 8). Pollution and cloud cover levels do not, however, contribute to intra-urban temperature variation at the block or neighborhood scales.

GIS data for both wind and traffic was actively sought for individual urban canyons within Copenhagen. To model intra-urban traffic variation as a dependent variable, traffic count data could indicate to what degree individual streets are used by motor vehicles, which emit heat as a byproduct of fossil fuel combustion. Combined with speed limit data, it would be possible to assign some measure of traffic intensity to each urban canyon. Although speed limit data was obtained, proprietary traffic count data could not be procured from the Copenhagen city government despite repeated attempts. Unlike traffic data, it appears that wind speed, frequency, and direction data does not exist for individual Copenhagen urban canyons. As a result of non-ideal building geometry, wind speeds, frequencies, and directions within Copenhagen are far from uniform. As such, before modeling the effect that wind has on intra-urban temperature variation, it would be necessary to empirically measure wind speed, frequency, and direction for a set of urban canyons by, for example, mounting two meteorological masts on each side of every canyon fixed with ultrasonic anemometers at several different altitudes (Nielsen 389-390).

Urban Canyon Selection

For the air temperature spatial data aggregation unit, 20 commercial/residential urban canyons were chosen from hundreds if not thousands of urban canyons from different neighbourhoods within Copenhagen. In other words, in this model, it was the air temperature of urban canyons that was used as the dependent variable. Urban canyons are the microscale urban form unit that comprise most of Copenhagen's neighborhoods. Urban canyons are where Copenhagen residents spend most of their time shopping, walking, working, socializing, and sleeping in the canyons' streets and buildings. For a multivariate regression model with three independent variables, a set of 20 cases is lower than ideal in quantity. Given the extensive GIS analysis that must be independently performed with each canyon's attribute data, however, adding canyons to the set is prohibitively time-consuming.

The selected urban canyons range in length from 106 to 315 meters with an average length of 190 meters as measured using ArcMap's measure tool. Prior to final selection, I visited each of the named urban canyons to verify general conformity to the urban form characteristics used to identify urban canyons. Effectively, each canyon is composed of a street navigable by both automobiles and pedestrians. Each canyon is also flanked by buildings on both sides, though side-street gaps regularly exist. Two-dimensional polygons were individually drawn around each canyon, excluding building masses, and added to a GIS layer file containing the entire set, shown in Figure 2.

Urban Canyon	Canyon Length (m)
Absalongade	147
Andreas Bjørns Gade	168
Augustagade	178
Blågårdsgade	220
Carl Johans Gade	151
Eckersbergsgade	142
Elmegade	230
Fælledvej	230
Jægersborggade	315
Jagtvej	166
Løngangstræde	136
Nørrebrogade	144
Oehlenshlægersgade	160
Slangerupgade	157
Sønder Boulevard	250
Studiestræde	315
Suensonsgade	190
Toftegards Alle	122
Værnedamsvej	180
Valkendorfsgade	106

Table 2: Selection of urban canyons with lengths

Figure 2: All Copenhagen urban canyons used in spatial statistics model

Temperature Data

LANDSAT surface temperature data was made available in raster format by GRAS, which had been previously used for the 2010 University of Copenhagen report. Using ArcMap's raster calculator tool, I converted the LANDSAT raster data from Kelvin scale surface temperature values to Celsius scale temperature values. One of the regression formulas given in the 2010 University of Copenhagen report relating surface and air temperature data was used to conduct a surface-to-air temperature conversion using the raster calculator. This equation ($y = .812x - 2.692$) was reported in the 2010 report with a coefficient of determination of .975 ("The University of Copenhagen" 26).

Rather than using data from every observation day included in the 2010 report, only temperature data from July 20th, 2006 was used as an urban canyon attribute in subsequent analysis steps. July 20th, 2006 was the hottest of the four 2006 observation days included in the 2010 University of Copenhagen report. As previously mentioned, however, the hottest areas in the city were the same on all four observation days.

To calculate the mean air temperature from July 20th, 2006 for each of the 20 urban canyon polygons, ArcMap's spatial analyst zonal statistics tool was used with both the Celsius scale air temperature raster and urban canyon GIS layers loaded into ArcMap. The zonal statistics tool incorporated air temperature raster cells in its areal mean calculation where the majority of an air temperature raster cell data landed within the urban canyon polygon, thereby excluding some cells partially overlapping the canyon polygon. To maximize the incorporation of overlapping air temperature raster data cells, the air temperature raster was resampled from 60-meter x 60-meter cells (Figure 3) to 1-meter x 1-meter cells (Figure 4) using a bilinear technique, which is recommended for continuous data sets by Esri's ArcMap Resource Center website as of May 2012. The bilinear interpolation method determines the value for the new cell in reference to a weighted distance average of nearby cells.

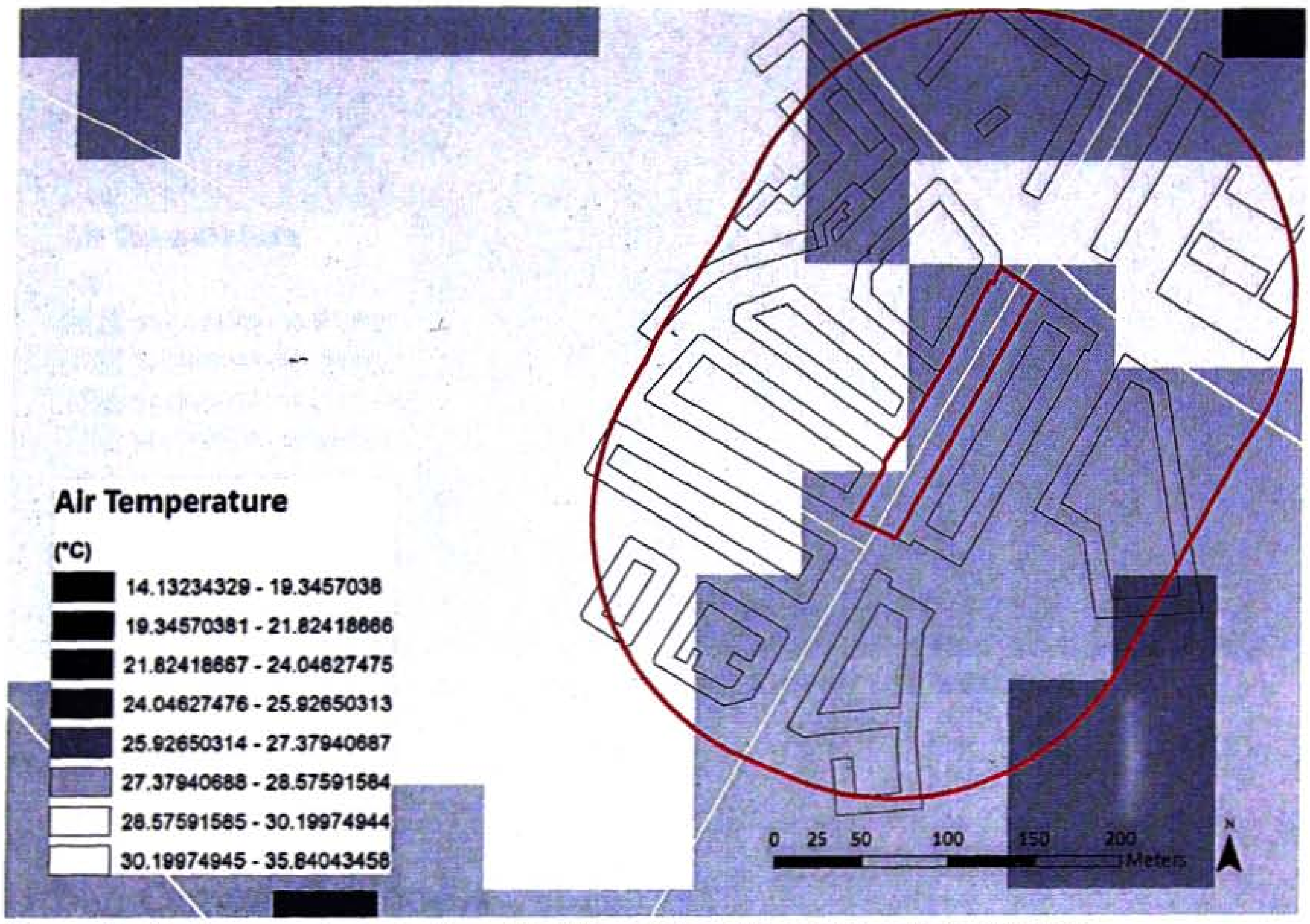


Figure 3: Air temperature raster with *60-meter x 60-meter cell resolution*

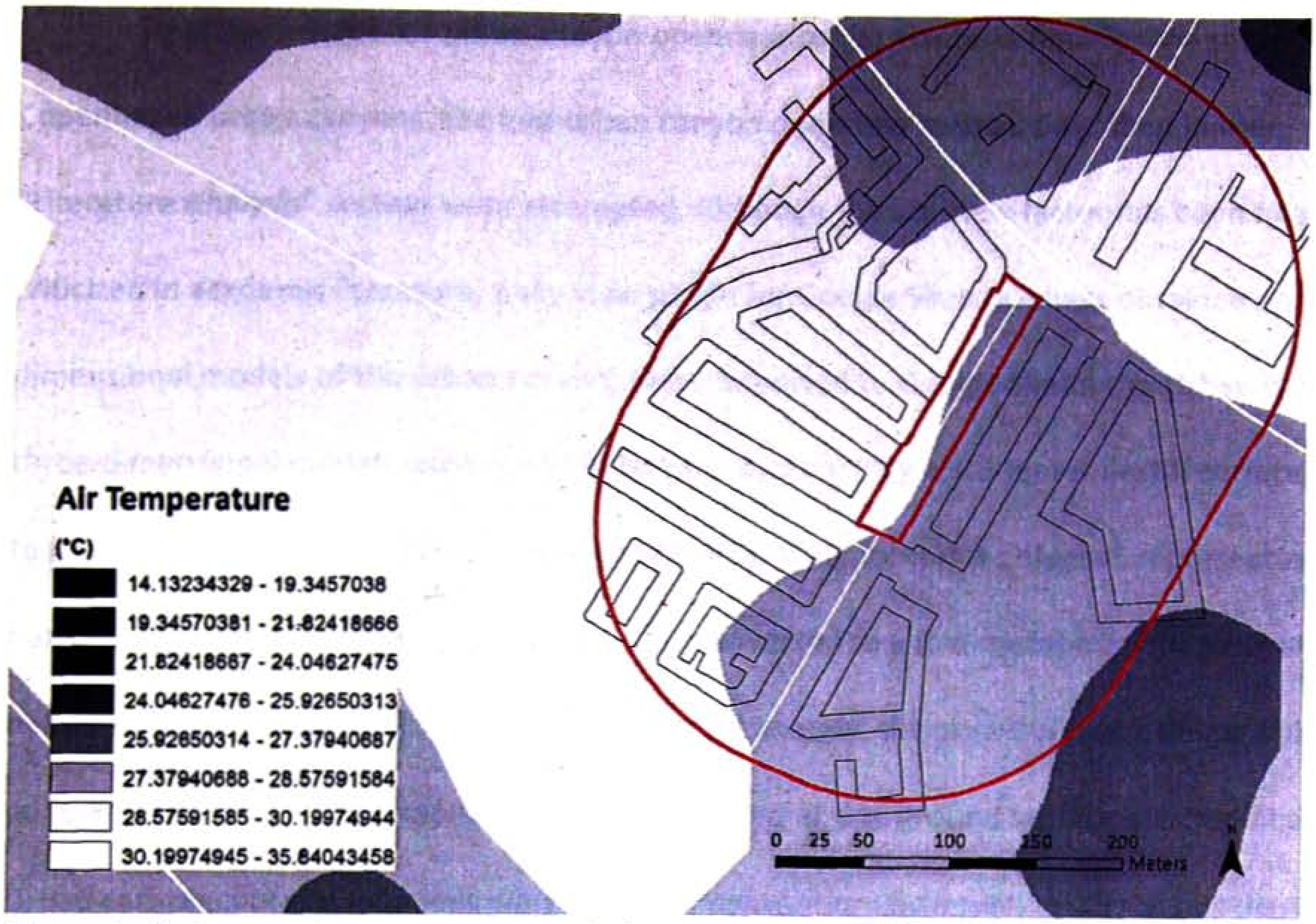


Figure 4: Air temperature raster resampled to 1 x 1 meter cell resolution

Urban Canyon Openness

Given the attention paid to urban canyon openness in urban climatology journals, such as *International Journal of Climatology*, *Theoretical and Applied Climatology*, and *Atmospheric Environment*, selecting urban canyon openness as a variable for modeling was an obvious choice when relevant data became available. A significant relationship between urban canyon openness and Copenhagen intra-urban air temperature would suggest how the degree to which buildings receive shortwave and/or trap longwave radiation affects canyon ambient temperature. Although the heights of buildings and widths of streets cannot be easily altered, results from the inquiry might indicate what type of canyons in Copenhagen should be targeted for cooling interventions.

To assign a value for urban canyon openness to the attribute field for the set of 20 Copenhagen urban canyons, the two urban canyon openness metrics described in the "Literature Analysis" section were attempted. Although the sky view factor has been heavily criticized in academic literature, a sky view plugin for Google SketchUp was obtained and three-dimensional models of the urban canyons were imported to Google SketchUp. Urban canyon three-dimensional models were made in ArcMap by attaching a 1.6-meter digital surface model to both the urban canyon layer polygons and the building footprint polygons representing their flanking buildings. This intermediate layer was converted to a five-meter interval contour layer before being imported to Google SketchUp. Unfortunately, the sky view factor plugin only permits for one sky view factor value to be calculated at one ground surface location at a time. Urban canyon centroid locations were used per convention; however, Lindberg's Gothenburg study had previously shown that an areal mean of sky view factor readings within an urban canyon correlates more strongly with intra-urban temperature variation than when only one sky view factor value is used (264). Furthermore, it was not possible to incorporate street trees into the Google SketchUp models that would have affected sky view factor measurements.

The height-to-width ratio metric is likewise susceptible to criticism given that it does not account for trees that may trap outgoing longwave radiation. The height-to-width ratio metric does, however, represent an average openness for the entire canyon of inquiry. As such, the height-to-width ratio metric was ultimately selected as the metric to represent the urban canyon openness independent variable.

To estimate the width of each canyon, ArcMap's measuring tool was used to determine the canyon's width at its centroid. It would have been possible to use road width values from municipal spatial data, but that would have ignored the presence of sidewalks. To calculate average canyon heights in ArcMap, polygons were drawn around the buildings flanking each canyon in the 20 urban canyon layer, not excluding voids where side streets adjoin the canyon streets. Next, 1.6-meter digital surface model and 1.6-meter digital terrain model rasters were attached to the flanking building-side street gap polygons. Using ArcMap's zonal statistics tool, the positive difference between the attached digital surface model and digital terrain model raster values represented the mean height of each canyon. Finally, the mean height of each canyon was divided by its centroid width to calculate a height-to-width ratio value for each of the 20 urban canyons.

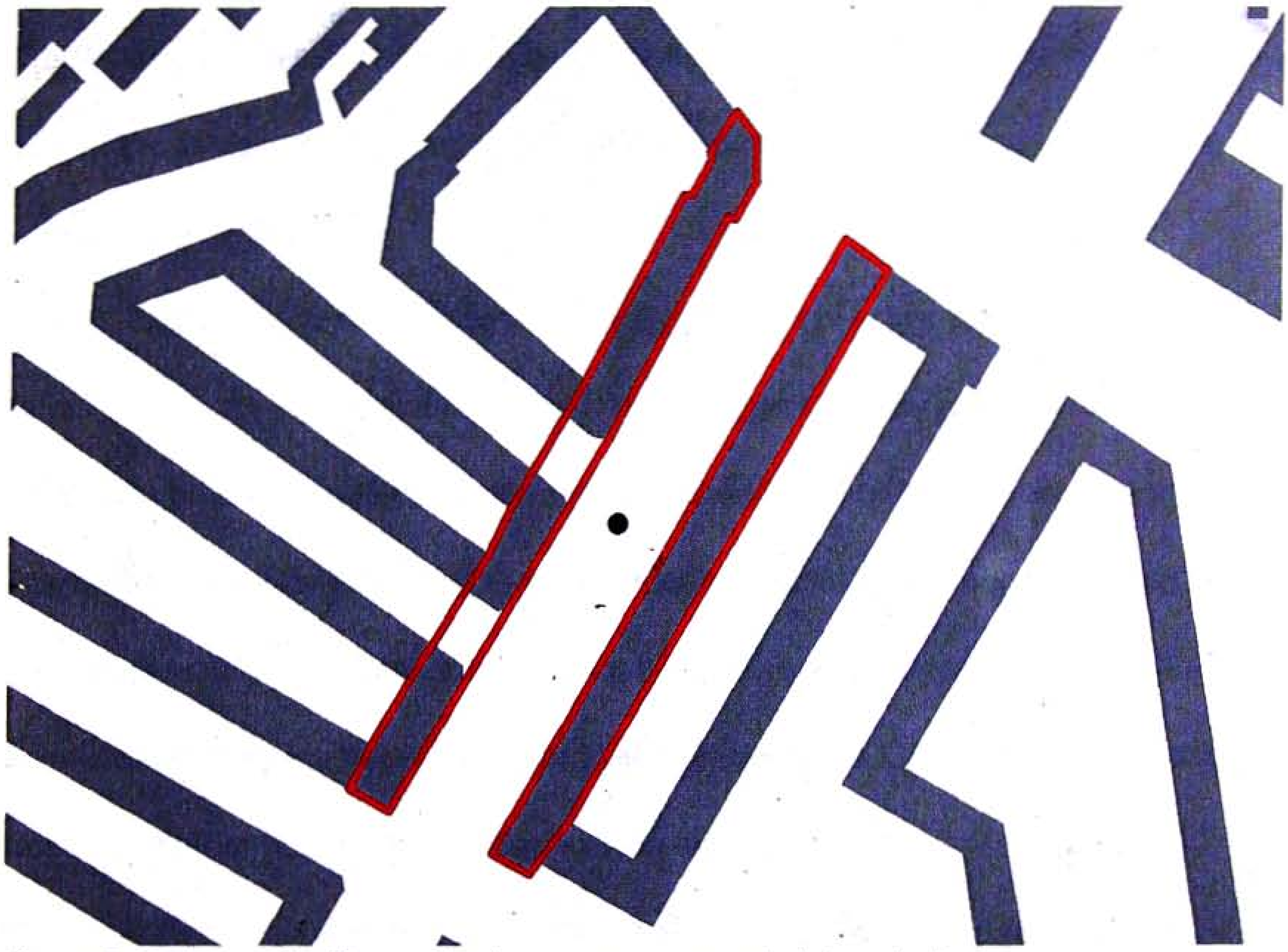


Figure 5: Polygons for (Jagtvej) urban canyon mean height calculation

Normalized Difference Vegetation Index

The 2010 University of Copenhagen report concluded that, on average, 44% of the variation in surface temperature at any given site in Copenhagen could be attributed to the change in the Normalized Difference Vegetation Index level at that site ("The University of Copenhagen" 38). The Normalized Difference Vegetation Index GIS data used for the 2010 report was again provided by GRAS in raster format for the four 2006 observation days. The 2010 report had tested the correlation between 60-meter x 60-meter surface temperature cell data and 30-meter x 30-meter Normalized Difference Vegetation Index cell data for the entire city. By examining the influence that variation in Normalized Difference Vegetation Index levels has on the average air temperature of urban canyons, similar correlative results on a different scale were expected.

Preliminary research into the cooling potential of urban parks and other forms of green infrastructure suggested that the extent of cooling provided by green infrastructure may extend beyond its boundaries. As such, two different Normalized Difference Vegetation Index aggregation units were included as independent variables in the model. The first unit was the average Normalized Difference Vegetation Index level of the urban canyon itself. Secondly, the Normalized Difference Vegetation Index level average for a 150-meter buffer extending out from the exterior border of the urban canyon was included.

Before calculating the average Normalized Difference Vegetation Index levels for each aggregation unit, the 30-meter x 30-meter Normalized Difference Vegetation Index data cells were re-sampled to one-meter x one-meter cells to promote maximum overlapping data inclusion. This re-sampling step was done as a result of anticipating similar results when using ArcMap's zonal statistics tool as were observed when using the zonal statistics tool to calculate the average air temperature of each urban canyon. Figures 6 and 7 display the Normalized Difference Vegetation Index raster data layers before and after re-sampling, respectively.

Prior to calculating the average Normalized Difference Vegetation Index level for each aggregation unit employing ArcMap's zonal statistics tool, all NoData cells from the original raster data provided by GRAS were removed. Though it would have been possible to generate a value for NoData cells using any number of averaging techniques, they were omitted for the following reasons: 1) NoData cells represent surfaces where biomass is undetected (water, asphalt, etc.) 2) NoData cells represented at most 7% of all cells eligible for inclusion in the averaging calculations and 3) per GRAS employee Rasmus Borgstrøm (personal communication 12/15/2011), NoData cells were not included in any of the calculations for the 2010 University of Copenhagen report. The implication of this omission is that Normalized Difference Vegetation Index level averages might be slightly higher than if NoData cells had been converted to numeric data cells and included in zonal statistics averaging calculations.

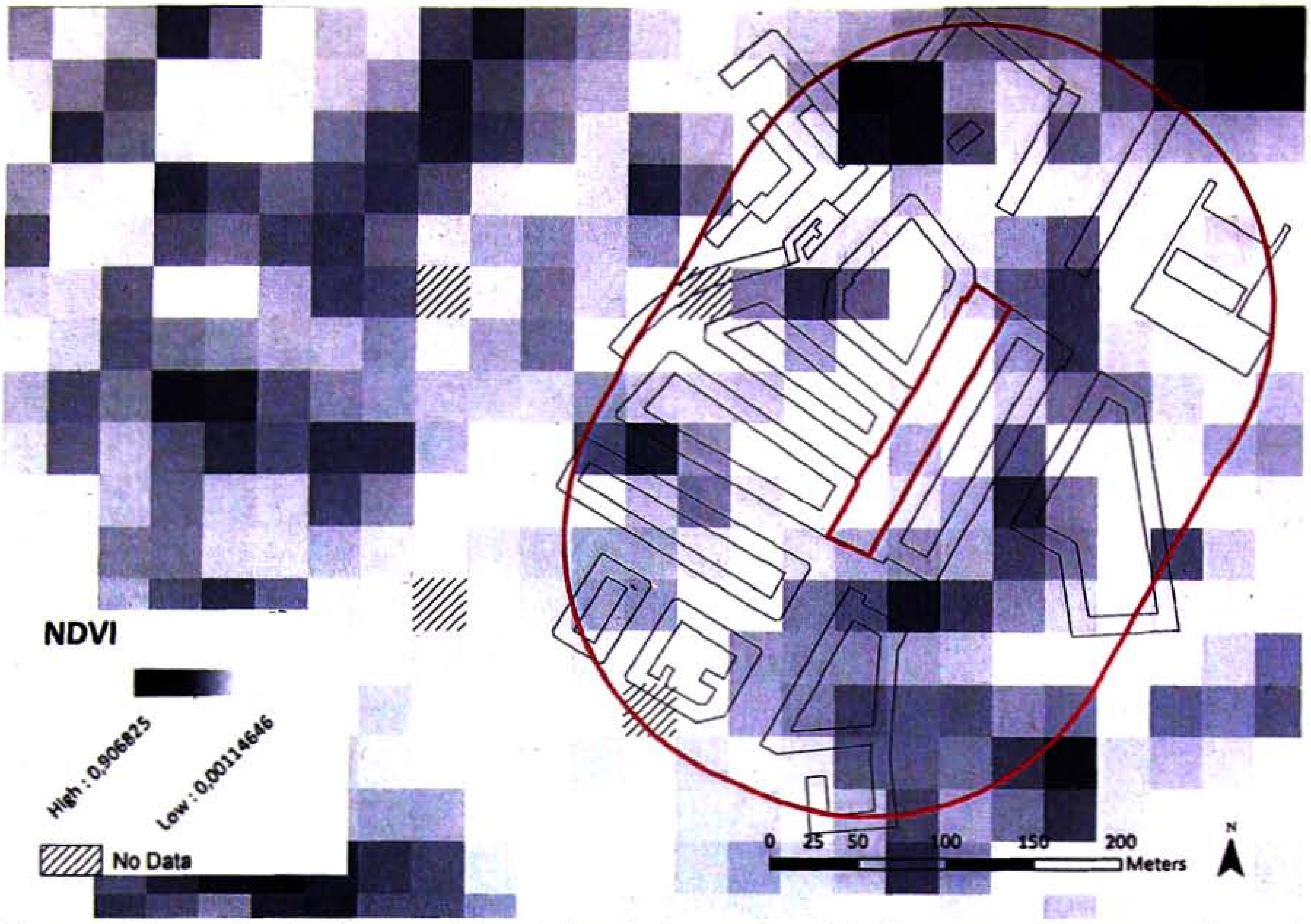


Figure 6: Normalized Difference Vegetation Index raster with 30-meter x 30-meter cell resolution

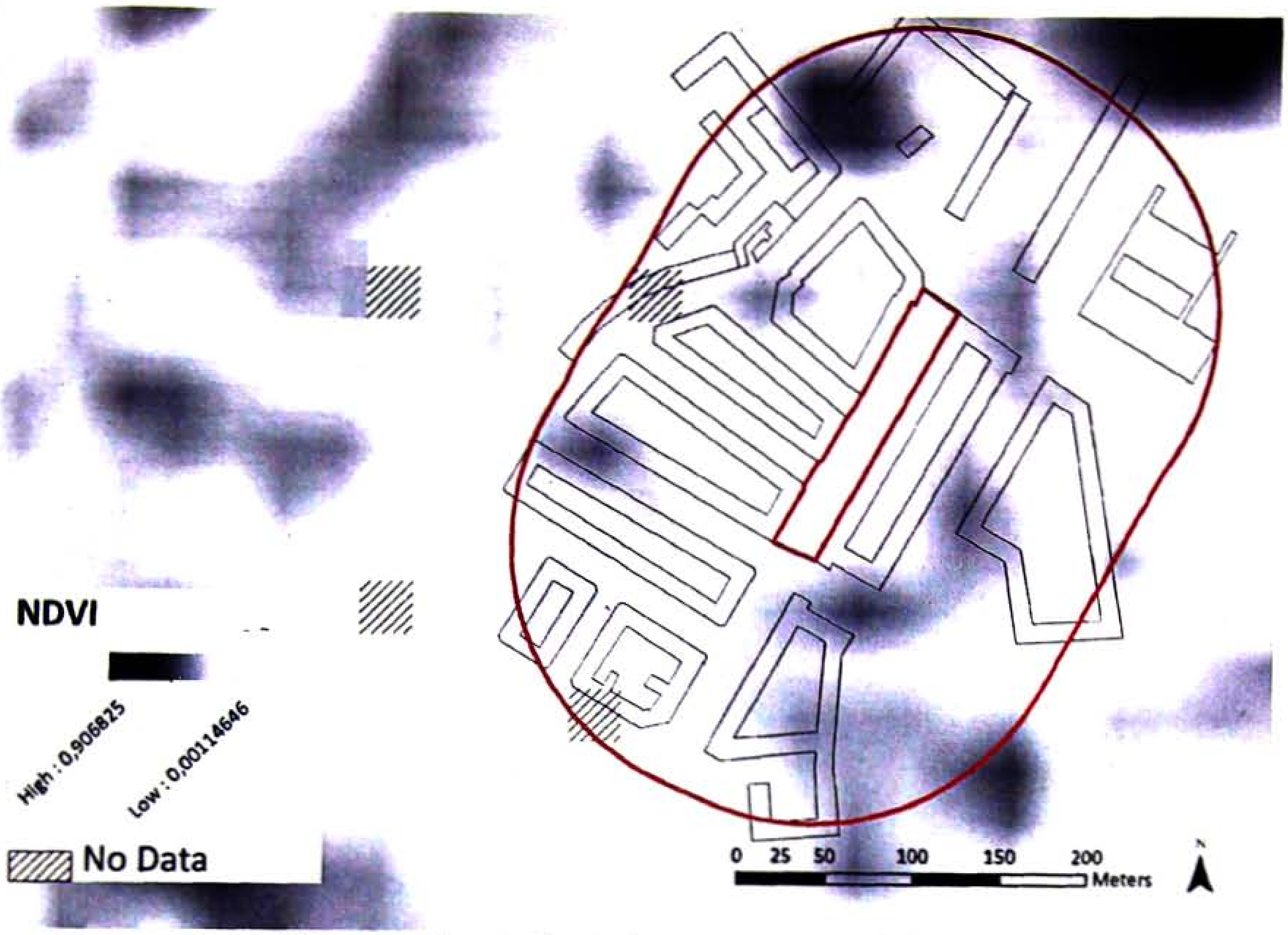


Figure 7: Normalized Difference Vegetation Index raster resampled to 1-meter x 1-meter cell resolution

Calculation Results

The previous subsections identify which urban surface energy variables were selected for inclusion as independent variables in a model placing urban canyon air temperature variation as the dependent variable. These subsections also explain how attribute data for each variable was calculated using GIS data with ArcMap. This attribute data was individually calculated for each of the 20 urban canyons selected for the study and is summarized in Table 3.

Urban Canyon Name	Canyon Mean Air Temp (°C)	Canyon Height-to-Width Ratio	Average Buffer Normalized Difference Vegetation Index	Average Canyon Normalized Difference Vegetation Index
Absalongade	29.65	1.40	0.14	0.20
Andreas Bjørns Gade	26.18	1.18	0.20	0.09
Augustagade	27.43	1.05	0.25	0.22
Blågårdsgade	27.29	1.06	0.24	0.27
Carl Johans Gade	27.99	1.12	0.17	0.14
Eckersbergsgade	27.45	0.57	0.23	0.28
Elmegade	28.78	1.45	0.19	0.20
Fælledvej	28.92	0.86	0.17	0.19
Jægersborggade	28.75	1.05	0.30	0.15
Jagtvej	28.58	0.65	0.17	0.11
Løngangstræde	28.83	1.35	0.08	0.10
Nørrebrogade	28.80	0.90	0.19	0.12
Oehlenshlægersgade	28.61	1.54	0.22	0.25
Slangerupgade	29.30	0.77	0.15	0.14
Sønder Boulevard	28.95	0.38	0.18	0.11
Studiestræde	28.79	1.26	0.11	0.10
Suensonsgade	27.87	0.38	0.17	0.16
Toftegards Alle	28.53	0.72	0.18	0.21
Værnedamsvej	28.92	1.19	0.16	0.05
Valkendorfsgade	29.28	2.08	0.09	0.05

Table 3: Urban canyon attribute data

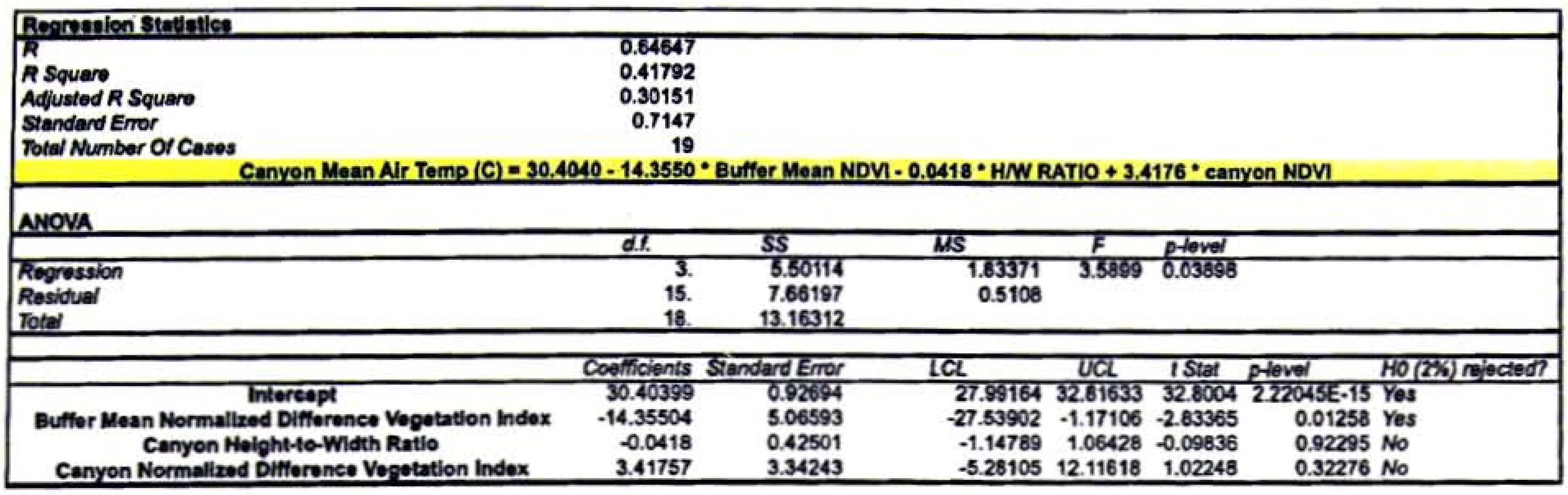
Removing Outliers

The average Normalized Difference Vegetation Index 150-meter buffer value for one urban canyon, Jægersborggade, was more than two times the standard deviation from the set mean. Therefore, Jægersborggade was identified as an outlier and removed from the set. No other outliers were identified after examining all variable values for each canyon. To explain the conditions of the outlier, one can observe that Jægersborggade abuts the Assistens Cemetery, which is a highly vegetated, walled-in green space. The Jægersborggade 150-meter buffer not only had the highest buffer Normalized Difference Vegetation Index value, but also had an above-average mean air temperature value. Whereas vegetation within the cemetery may have contributed to a relatively high buffer Normalized Difference Vegetation Index value reading, the cemetery walls may stifle wind from transporting cool air from the cemetery to the Jægersborggade urban canyon, where there are no street trees.

Figure 8: Jægersborggade urban canyon looking towards Assistens Cemetery

Multivariate Regression Analysis

A multivariate regression analysis for the 19 remaining urban canyons was conducted using Microsoft Excel with the calculations summarized in Table 3. The independent variable was urban canyon mean air temperature. The three initial independent variables were mean urban canyon Normalized Difference Vegetation Index, mean 150-meter buffer Normalized Difference Vegetation Index, and urban canyon height-to-width ratio. A summary of results for the first interpretation of the model is displayed in Table 4. Residual plots confirming linearity, homoskedasticity, and nonautoregressivity for all three independent variables included in the first interpretation of the model are displayed in Figures 9, 10, and 11. Next, the three independent variables were tested for multicollinearity using a Pearson's r test, the result of which are summarized in Table 5. In the second interpretation of the model, the mean urban canyon Normalized Difference Vegetation Index variable was omitted. A summary of results for the second interpretation of the model is displayed in Table 6.



Regression Statistics	
R	0.64647
R Square	0.41792
Adjusted R Square	0.30151
Standard Error	0.7147
Total Number Of Cases	19

Canyon Mean Air Temp (C) = 30.4040 - 14.3550 * Buffer Mean NDVI - 0.0418 * H/W RATIO + 3.4176 * canyon NDVI

ANOVA	*d.f.*	*SS*	*MS*	*F*	*p-level*
Regression	3.	5.50114	1.83371	3.5899	0.03898
Residual	15.	7.66197	0.5108		
Total	18.	13.16312			

	Coefficients	*Standard Error*	*LCL*	*UCL*	*t Stat*	*p-level*	*H0 (2%) rejected?*
Intercept	30.40399	0.92694	27.99164	32.81633	32.8004	2.22045E-15	Yes
Buffer Mean Normalized Difference Vegetation Index	-14.35504	5.06593	-27.53902	-1.17106	-2.83365	0.01258	Yes
Canyon Height-to-Width Ratio	-0.0418	0.42501	-1.14789	1.06428	-0.09836	0.92295	No
Canyon Normalized Difference Vegetation Index	3.41757	3.34243	-5.28105	12.11618	1.02248	0.32276	No

Table 4: Multivariate regression results for first interpretation of model

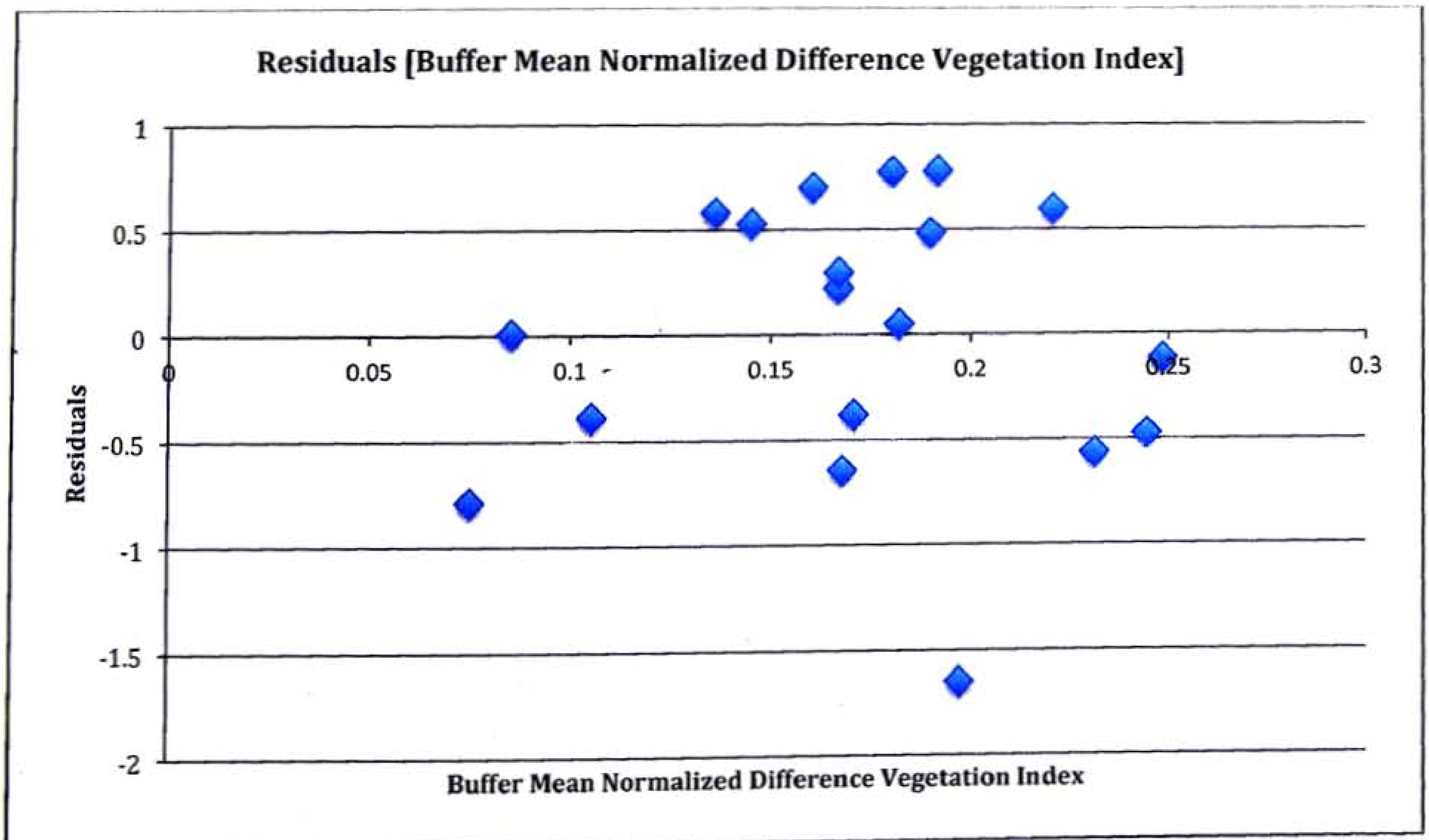


Figure 9: Residual plot for 150-meter buffer Normalized Difference Vegetation Index variable data

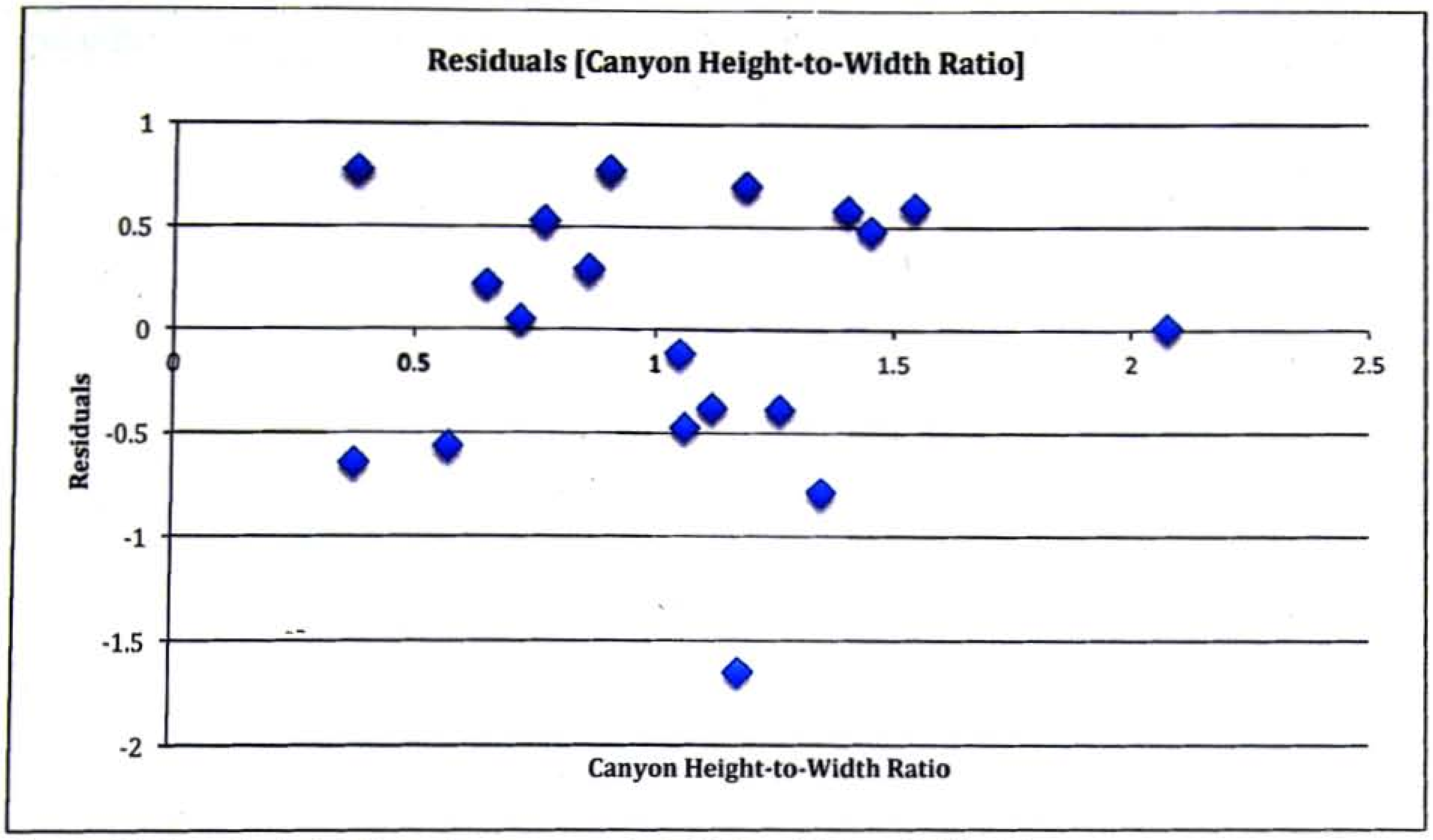


Figure 10: Residual plot for urban canyon height-to-width variable data

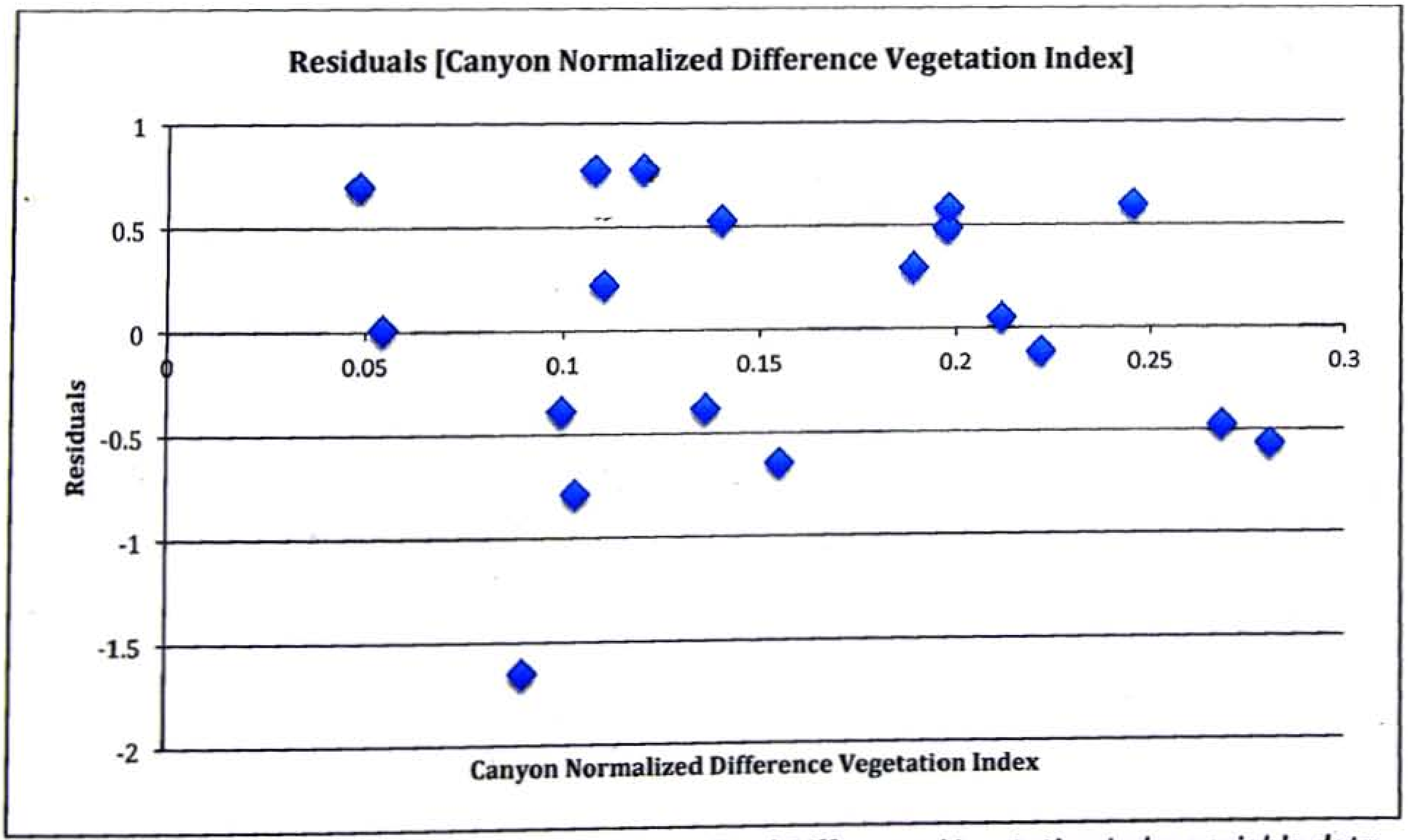
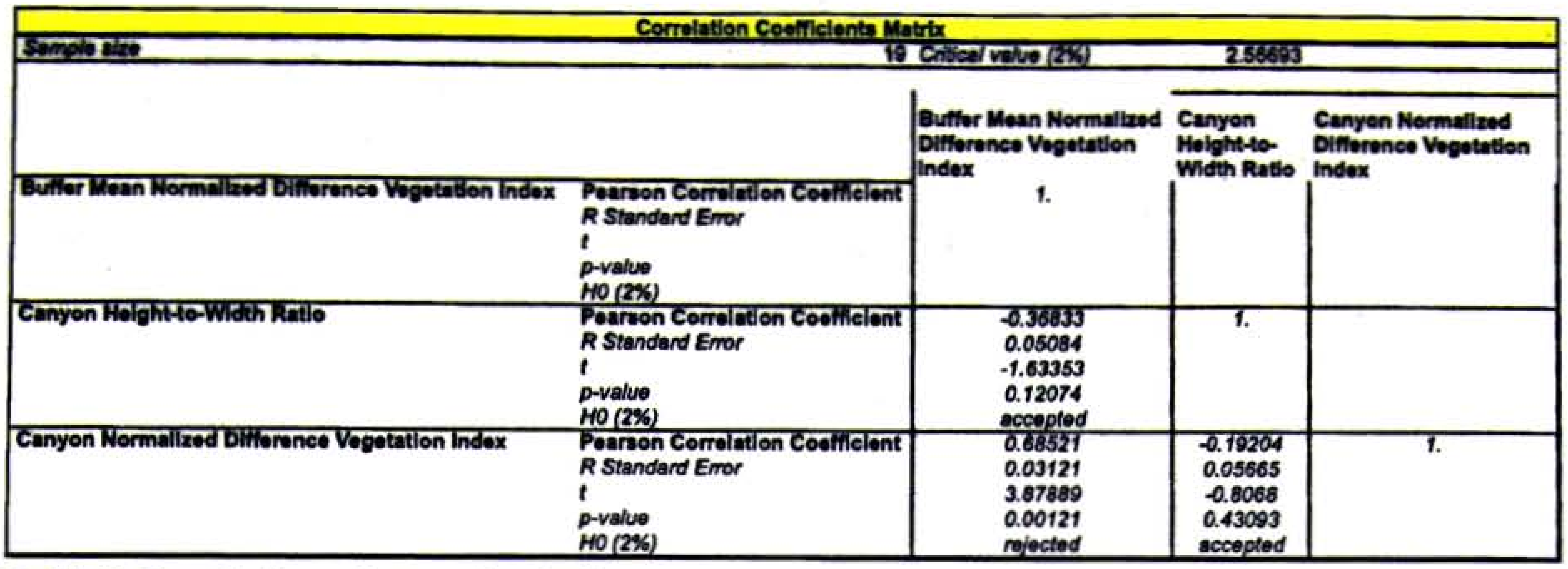
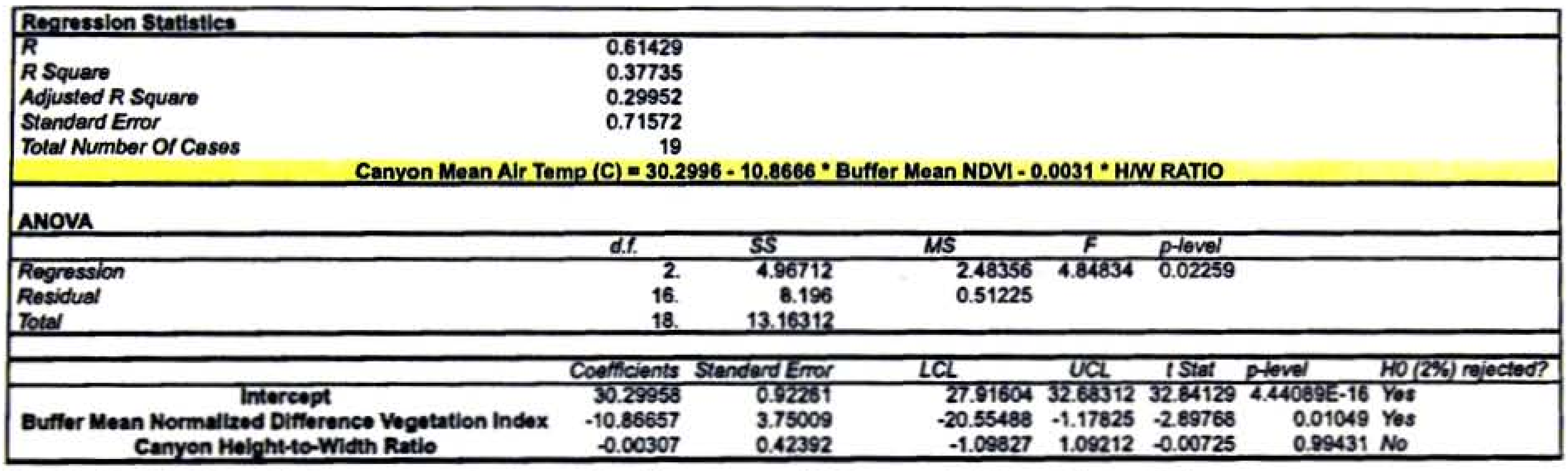


Figure 11: Residual plot for urban canyon Normalized Difference Vegetation Index variable data



Correlation Coefficients Matrix				
Sample size	19	Critical value (2%)	2.56693	
		Buffer Mean Normalized Difference Vegetation Index	Canyon Height-to-Width Ratio	Canyon Normalized Difference Vegetation Index
Buffer Mean Normalized Difference Vegetation Index	**Pearson Correlation Coefficient**	1.		
	R Standard Error			
	t			
	p-value			
	H0 (2%)			
Canyon Height-to-Width Ratio	**Pearson Correlation Coefficient**	-0.36833	1.	
	R Standard Error	0.05084		
	t	-1.63353		
	p-value	0.12074		
	H0 (2%)	accepted		
Canyon Normalized Difference Vegetation Index	**Pearson Correlation Coefficient**	0.68521	-0.19204	1.
	R Standard Error	0.03121	0.05665	
	t	3.87889	-0.8068	
	p-value	0.00121	0.43093	
	H0 (2%)	rejected	accepted	

Table 5: Results from Pearson's r test



Regression Statistics	
R	0.61429
R Square	0.37735
Adjusted R Square	0.29952
Standard Error	0.71572
Total Number Of Cases	19

Canyon Mean Air Temp (C) = 30.2996 - 10.8666 * Buffer Mean NDVI - 0.0031 * H/W RATIO

ANOVA	*d.f.*	*SS*	*MS*	*F*	*p-level*
Regression	2.	4.96712	2.48356	4.84834	0.02259
Residual	16.	8.196	0.51225		
Total	18.	13.16312			

	Coefficients	*Standard Error*	*LCL*	*UCL*	*t Stat*	*p-level*	*H0 (2%) rejected?*
Intercept	30.29958	0.92261	27.91604	32.68312	32.84129	4.44089E-16	Yes
Buffer Mean Normalized Difference Vegetation Index	-10.86657	3.75009	-20.55488	-1.17825	-2.89768	0.01049	Yes
Canyon Height-to-Width Ratio	-0.00307	0.42392	-1.09827	1.09212	-0.00725	0.99431	No

Table 6: Multivariate regression results for second interpretation of model

DISCUSSION

Statistical Analysis

In the first interpretation of the model, the coefficient of determination was .42, indicating that 42% of urban canyon air temperature variation was determined by variation amongst the three independent variables. Although the null hypothesis could be rejected for the model, it could not be rejected for either the canyon height-to-width ratio or canyon mean Normalized Difference Vegetation Index variables individually. The decision to omit the canyon mean Normalized Difference Vegetation Index for the second interpretation of the model was based on both the variable's null hypothesis result as well as the results of the Pearson's r test, which indicated a Pearson Correlation Coefficient of .69 for the mean urban canyon and mean buffer Normalized Difference Vegetation Index variables. It was not entirely surprising that such a high level of collinearity was observed between the two Normalized Difference Vegetation Index variables given that they were derived from the same parent metric.

In the second interpretation of the model, the coefficient of determination was .38, indicating that 38% of urban canyon air temperature variation was determined by variation amongst the two independent variables. Once again, the null hypothesis was rejected for the model but not for the height-to-width ratio variable. Given the extensive attention paid to urban canyon openness by urban climatology research, it was surprising to find a statistically insignificant relationship between the urban canyon height-to-width ratio variable and urban canyon air temperature. Although the ratio of height-to-width undoubtedly influences the temperature of Copenhagen's individual urban canyons, Copenhagen's relatively uniform building heights may explain why variation in urban canyon height-to-width ratios does not affect urban canyon temperature variation. Another explanation might be that the temperature data used in both the analysis was not limited to the later hours of the day, when longwave radiation is re-emitted into urban canyons at a higher rate than earlier in the day. Lastly, it's possible that increases in temperature as a result of longwave radiation trapping within Copenhagen urban canyons are negated by relatively tall urban canyon heights, which provide daytime shading in narrower canyons, thereby preventing shortwave radiation from entering the canyons in the daytime.

As the null hypothesis was rejected for the buffer mean Normalized Difference Vegetation Index variable for both the first and second interpretations of the model, it can be asserted that there is a statistically significant relationship between mean buffer Normalized Difference Vegetation Index levels and Copenhagen urban canyon mean air temperature variation. Coefficients of determination for the first and second interpretations of the model of .42 and .38, respectively, suggest that more than one-third of Copenhagen urban canyon mean air temperature variation is affected by the variation of buffer mean Normalized Difference Vegetation Index levels. These R squared values are also consistent with the .44 average R square value reported in the University of Copenhagen's 2010 report correlating Copenhagen surface temperature and Normalized Difference Vegetation Index levels.

The second model interpretation indicates that for every dimensionless unit of increase in the mean Normalized Difference Vegetation Index of the 150-meter buffer surrounding an urban canyon, a decrease in mean urban canyon air temperature of 10.87 °C can be expected. However, the range of variation in mean Normalized Difference Vegetation Index of the 19 included 150-meter buffers is .22, just above one-fifth of one dimensionless Normalized Difference Vegetation Index unit. As such, reductions in mean air temperature of the 19 urban canyons as a result of green infrastructure interventions in the 150-meter buffers surrounding an urban canyon could be as much as several degrees Celsius, which would be sufficient to reduce the risk of heat exhaustion or heat stroke within Copenhagen urban canyons during a summertime heat wave.

Green Infrastructure Introduction

The results of the statistical analysis suggest that significant cooling to a Copenhagen urban canyon can be created by increasing the level of vegetation in the area surrounding the canyon up to a distance of at least 150 meters. Other climatic and urban form characteristics associated with the urban surface energy balance equation that were not included in the statistical model are also likely to contribute to the air temperature variation in Copenhagen's urban canyons. Given the R square values of the two interpretations of the multivariate regression model, however, there is reason to further consider how green infrastructure might assist in reducing Copenhagen's urban heat island effect as manifested within urban canyons.

Because cooling within canyons can be expected originating from sources outside of the canyon itself, the conditions under which vegetation generates cool air drifting beyond its immediate location is relevant. Generally speaking, vegetation is known to create cool air via evapotranspiration that is transported by wind. The green infrastructure elements capable of producing cool air via evapotranspiration that will be addressed here are urban parks, street trees and green roofs as these three elements have been most studied. Although I was able to find one academic journal article on the cooling potential of green walls, I could not find sufficient information to comment on the cooling potential of green walls herein. Unfortunately, I was unable to locate any academic journal articles regarding the cooling potential of Sustainable Urban Drainage Systems.

Urban Parks

Urban parks are perhaps the most promising green infrastructure element that can be introduced to cool nearby urban canyons. Vegetation comprising urban parks reduces near-surface air temperatures by evapotranspiring moisture, reflecting incoming solar radiation, and shading materials that might otherwise absorb and re-emit solar radiation. Urban parks might be placed in any vacant or under-utilized space in close proximity to where urban canyon cooling is desired. If the results from the present study are to be trusted, then effective cooling can be expected where an urban park is sited within a 150-meter buffer of the urban canyon. Many other researchers have reported a cooling effect derived from urban parks extending beyond their boundaries (Dimoudi and Nikolopoulou 75; Ng et al. 261; Oliveira, Andrade, and Vaz 2186-2194). This phenomenon helps to explain why the air temperature variation of Copenhagen urban canyons is affected by the relative amount of peripheral vegetation surrounding them.

When deciding where to site an urban park, there are several important criteria to consider, beginning with the direction that cool air generated by that park is likely to travel. An urban park's cooling effect will horizontally extend to the leeward side a distance up to one park width or diameter from its boundary (Dimoudi and Nikolopoulou 75; Spronken-Smith and Oke 309). As such, an urban park should be placed upwind of the urban canyon for which it is intended to cool. To measure the direction of prevailing wind of an area surrounding an urban canyon, ultrasonic anemometers can be placed in and around the canyon.

Secondly, it is critical to consider how far cool air generated within an urban park is capable of traveling. As mentioned, one can assume that the cooling potential of a park extends a distance of one park width from its boundary. An urban park that is 100 meters wide, for example, can be expected to cool the downwind urban fabric surrounding it for a distance up to

100 meters from its edge. Studies have shown, in fact, that even parks as small as 60-meters x 40-meters will generate measurable cooling on the leeward side beyond their boundaries (Saito, Ishihara, and Katayama 497). A Lisbon study found that urban street air temperatures were reduced along a 570-meter path from the boundary of a relatively small .24-ha urban park (Oliveira, Andrade, and Vaz 2186-2194). In London, Watkins found that a case study street downwind of an urban park was cooled for a distance of up to 400 meters as a result of its proximity to the park.

The quantity of cool air that can be transported by wind from a park into the urban fabric is initially dependent on the amount of cool air present within the park. As Spronken and Oke pointed out, a larger park is likely to generate a greater quantity of cool air available for transport (309). In addition to maximizing a park's size, there are several other structural issues to consider when trying to encourage the availability of cool air for transfer to an urban canyon. As by a Hong Kong mesoscale empirical observation/numeric modeling study, a park with more trees is likely to be cooler than a park predominated by grasses (Ng et al. 256-271).

If cool air is desired during the daytime for transport to urban canyons where this significant daytime pedestrian activity, then well-irrigated parks are appropriate given that moisture is a limiting factor for evapotranspiration, which peaks during the day. Shade-providing trees should also be prevalent in a park for which daytime cooling is demanded in order to maximize shortwave radiation reflection and shading. If, in contrast, cool air is desired during the nighttime for transport to residential urban canyons, a more open park is appropriate as large trees tend to slow the process by which a park cools down at night by obstructing re-emitted longwave radiation (Spronken-Smith and Oke 288-309).

Green Roofs

Green roofs, like urban parks, can provide space for vegetation within the existing urban fabric. Pompeii and Hawkins conducted a hardware scale model study that found daytime outdoor temperatures to be cooler in a simulated built environment when green roof materials were used instead of standard roofing materials (Pompeii and Hawkins 54). Using a numeric modeling scheme, Bass found that if 5% of Toronto's existing roof cover was converted to green roof cover, a .5-degree Celsius air temperature reduction at the mesoscale could be expected. Like urban parks, green roofs generate cool air via the evapotranspiration mechanism inherent to vegetation. Green roofs also add a layer of insulation to a building, which may reduce heat gain within a building or, problematically, increase the nighttime interior temperature of the building under some circumstances (Pompeii and Hawkins 52-61). Unfortunately, I was unable to locate any studies regarding the potential for green roofs to cool the interior of buildings via the evapotranspiration mechanism of vegetation inherent to green roofs.

When selecting a building in an urban canyon for green roof installation, one should consider the size of the building footprint. As with urban parks, a larger green roof is likely to generate a higher quantity of cool air available for transport to the pedestrian street level of its building, where outdoor cooling is desired. The site selection process for a green roof installation differs from that for an urban park in that the height of the prospective building relative to the urban canyon's width must be considered. Cool air from a green roof on a very tall building may never reach the ground surface, as was observed in a Hong Kong study by Ng et al., who suggest that when the building-height-to-street width ratio exceeds one, there will be minimal cooling at the pedestrian level (270). As such, relatively short urban canyon buildings with large footprints should be targeted for green roof installation if pedestrian street-level cooling is desired. To what degree cool air generated by green roofs is carried horizontally by wind was not found in a literature survey.

Street Trees

Street trees can reduce urban canyon air temperatures by reflecting incoming shortwave radiation and generating cool air via evapotranspiration. As with green roofs, it is unclear as to whether or not cooling generated by street trees is carried horizontally by wind to nearby locations. Nonetheless, many studies have shown the cooling benefits of street trees to the urban canyons in which they stand (Oliveira, Andrade, and Vaz 2192). A Sao Paulo, Brazil study, for example, used numeric modeling to demonstrate that urban canyons with trees were, on average, .5 to 1.1°C cooler than similar canyons without trees (Ng et al. 261-262). To maximize the evapotranspiration potential of street trees, one might consider the surfaces beneath street tree canopies. Kjelgren and Montague, for example, compared the evapotranspiration performance of trees planted over asphalt and turf grass surfaces; unfortunately, their results were inconclusive (Arnfield 10). More studies should be conducted to measure horizontal cooling transfer and examine which surfaces and tree species are most conducive to effective air temperature reduction. Although I was unable to locate any relevant information, It is possible that pertinent literature regarding potential horizontal cooling transfer of street trees exists on the United States Forest Service's "i-Tree" website, a reference and application guide website for urban foresters.

There are some complicating factors associated with street trees that should be contextually researched before they are installed within or near an urban canyon strictly for cooling purposes. In a relatively tall, narrow urban canyon, for example, street trees may, like buildings, trap re-emitted longwave radiation from exiting the canyon, thereby contributing to a nocturnal urban heat island effect. In this regard, street trees affect the sky view factors of the urban canyons in which they stand. Given that street trees both reflect incoming shortwave radiation and evapotranspire, however, their net effect on the air temperature of a tall, narrow urban canyon may still be negative (i.e. may still provide net cooling). Finally, it is important to recognize that street trees are, like any object, capable of blocking wind. As such, it is possible that street trees placed at the entrance of an urban canyon could prevent cool air from being transported into the canyon from external locations. Therefore, for urban canyons where prevailing wind conditions are known to transport cool air into urban canyons, street trees should be placed away from the entrance where cool air enters. If street trees are nevertheless desired at the entrance of windy canyons, tree species with canopies that allow for more wind to pass through them could be selected.

Despite these complicating factors, street trees are generally considered to make positive contributions to street cooling and urban heat island effect reduction. Stone and Norman used remote sensing to find that street tree canopies reduce the urban heat island effect in Atlanta by shading surfaces (Stone and Norman 3561-3573). Interestingly, in their hardware scale model, Spronken-Smith and Oke found that clusters of trees reduce the urban heat island to a greater degree than individual street trees (287-312). Effectively, when designing a street tree intervention intended to cool an urban street or canyon, it may be beneficial to cluster trees to provide large swaths of shaded surface.

Using a numeric microscale model, Dimoudi and Nikolopoulou found that tree shading intensity varies seasonally (69-76). In Copenhagen, where only seasonal cooling is desired, deciduous species should be selected that do not reflect shortwave radiation or evapotranspire at a significant level in the colder months. For Copenhagen urban canyons where cooling is never desired, however, street trees might be strategically placed to encourage warming. Large evergreen street trees that do not evapotranspire at a high rate might be placed to block prevailing winds from entering an urban canyon and trap outgoing longwave radiation from leaving the canyon.

Green Infrastructure Conclusion

Current research on the cooling potential of green infrastructure elements is primarily based on case study empirical observation research, hardware scale modeling, and numeric computer modeling. Studies have shown urban parks, green roofs, and street trees to have urban cooling potential in different idealized and location-specific contexts. More research is needed that would allow for practitioners to more readily interpret the findings of green infrastructure cooling potential research for any real world urban context.

At present, the horizontal transfer of cool air by urban parks is better understood than the potential for green roofs or street trees to generate cool air available for horizontal transfer. Further research on the potential for street trees and green roofs to contribute to block scale cooling should therefore be conducted. Given that the modeling study included herein indicated a statistically significant relationship between the level of vegetation in a 150-meter buffer surrounding 19 Copenhagen urban canyons, it would seem most logical to encourage the addition of urban parks to locations within 150-meters of Copenhagen urban canyons where cooling is desired.

General principles guiding the site selection and design of urban parks for cooling purposes are possible to discern from the literature surveyed. To begin, a site should be selected upwind of the urban canyon for which cooling is desired. The site should allow for a vegetated park with a diameter as least as long as the distance separating the edge of the park from the canyon's entrance. Generally speaking, a larger park with more trees than grasses is more likely to generate a larger amount of cool air available for horizontal transfer. The design of the park itself should also depend on the time of day that cooling is desired. To maximize nighttime cooling, a park with fewer trees capable of trapping longwave radiation should be constructed. To maximize daytime cooling, a park with large, shade-providing trees and water features, such as Sustainable Urban Drainage Systems, should be constructed.

Application

Although its possible to convey general principles regarding the cooling potential of green infrastructure elements based on a literature survey combined with a contextual GIS-based spatial statistics analysis, other modeling and observation methods can contribute more specific insight when evaluating their cooling potential for a specific urban context. Before making widespread green infrastructure interventions in and surrounding its urban canyons, for example, a city may desire to know how many degrees of cooling can be expected from such an investment. To this end, numeric modeling, hardware scale modeling, and empirical observation can contribute to more comprehensive predictive analysis.

Numeric Modeling

Numeric modeling allows for both surface urban form and local climatic characteristics to be input into computer simulations that output temperature change predictions. Several established models perform analyses at the neighborhood scale, such as the Local-Scale Urban Meteorological Parameterization Scheme, which can provide temperature prediction results at a scale of a few hundred square meters. Given the scale of this output, American Local-Scale Urban Meteorological Parameterization Scheme model studies have used census tracks as the principal spatial unit of data aggregation. Interestingly, the model was calibrated with field observations from seven North American cities (Miami, Mexico City, Vancouver, Tucson, Los Angeles, Sacramento, and Chicago) by Grimmond and Oke (792-810). The American Local-Scale Urban Meteorological Parameterization Scheme model requires metric inputs representing urban surface cover; surface roughness (building height and density); and local climatic conditions. In previous studies, the surface character of individual census tracks has been represented by the Normalized Difference Vegetation Index metric. The American Local-Scale Urban Meteorological Parameterization Scheme model output estimates hourly radiation flows partitioned into latent heat (Q_E), sensible heat (Q_H), and change in stored heat (Q_S).

A similar American freeware model is the National Center for Atmospheric Research Mesoscale Model. A three-dimensional fluid dynamics-based model capable of simulating interactions between a range of land surface cover and climatic variables, the National Center for Atmospheric Research Mesoscale Model assigns percentage values for impervious surface, grass, trees, and water to uniformly-sized grid cells (1.3-km cells). A 2009 urban heat island effect study employing the model for New York City used Normalized Difference Vegetation Index data to calculate land surface cover inputs. The influence of buildings was represented by an average surface roughness estimate. Amongst other outputs, the National Center for Atmospheric Research Mesoscale Model can generate air temperature change predictions (Rozenweig et al. 1302-1305).

Although mesoscale models have the advantage of predicting results for an entire city or metropolitan area, they overlook the influence of vegetation on immediate surroundings and fail to disambiguate temperature mixing zones resulting from wind (Ng et al. 260). The Local-Scale Urban Meteorological Parameterization Scheme model effectively emerges as the most promising numeric model given the scale at which it returns temperature change predictions.

Researchers interested in green infrastructure interventions In Copenhagen could alter surface cover inputs into the National Center for Atmospheric Research Mesoscale Model while keeping other parameters constant to evaluate how the balance between latent, sensible, and stored heat might be affected by changes to Normalized Difference Vegetation Index levels.

Hardware Scale Modeling

An alternative to numeric modeling is hardware scale modeling, which simulates interactions between heat exchange processes and surface-boundary conditions with dimensioned physical models. Although hardware scale models can capture real world urban surface energy balance interactions at the block scale, they do not mimic the complexities of an actual city's urban form in their simulation of idealized urban geometries. The open-air scaled urban surface model, for example, calls for an array of scaled buildings (2 x .2 x .4 meters) set in uniformly arranged rows. The open-air scaled urban surface model simulates the influence of evapotranspiration on temperature: water pans from which water loss is measured is taken to represent evapotranspiration activity. Output information from the open-air scaled urban surface model includes evaporation rates and building cooling demand with respect to wind direction and building geometry (Kruger and Pearlmutter 2091-2092).

Another hardware scale model example already mentioned was created by Pompeii and Hawkins to measure the effect of green roofs on urban microscale temperature variation. For this study, two model cities spanning approximately 16 square feet were constructed with buildings, sidewalks, and roads using real world construction materials (brick pavers, concrete pavers, roof felt, outdoor paint, and live plants). One model city was composed of green roof model buildings and the other with standard roof model buildings. HOBO Pro v2 data loggers collected temperature, humidity, and dew point data from the center of the model cities and temperature data from within the buildings (Pompeii and Hawkins 54-57). In Copenhagen, researchers could construct outdoor hardware scale models mimicking urban canyons to measure how additions of simulated green infrastructure affect air temperature within the model canyons.

Empirical Observation

In the Pompeii and Hawkins study described above, instruments were used to empirically measure several climate parameters in scale models. The process of empirical observation is likewise feasible at a larger, real world scale. Although empirical observation cannot describe the full complexity of the interaction between climate and urban form factors, it allows for data inquiry generally free of major assumptions. As such, it has become increasingly popular to use empirical observation in combination with and/or to verify results from numeric modeling. When used independently, on-site observation may prove incapable of isolating the effects of individual features, such as vegetation, given the complexity of interacting urban surface energy balance fluxes at or nearby measurement sites (Kruger and Pearlmutter 2090).

On-site measurement is possible with fixed or mobile equipment, such as bicycles. The goal of empirical observation of surface energy balance parameters may be, for example, to evaluate how urban canyon air temperatures respond to new green infrastructure elements. A 2011 study already mentioned that was conducted by Oliveira, Andrade, and Vaz, for instance, investigated the thermal effects of a .24 ha Lisbon urban park on the surrounding city blocks. Measurements were taken of microclimate parameters (temperature, relative humidity, wind speed, solar, and infrared radiation) along a 570-meter path at eight locations of varying orientation and increasing distance from the center of the park (Oliveira, Andrade, and Vaz

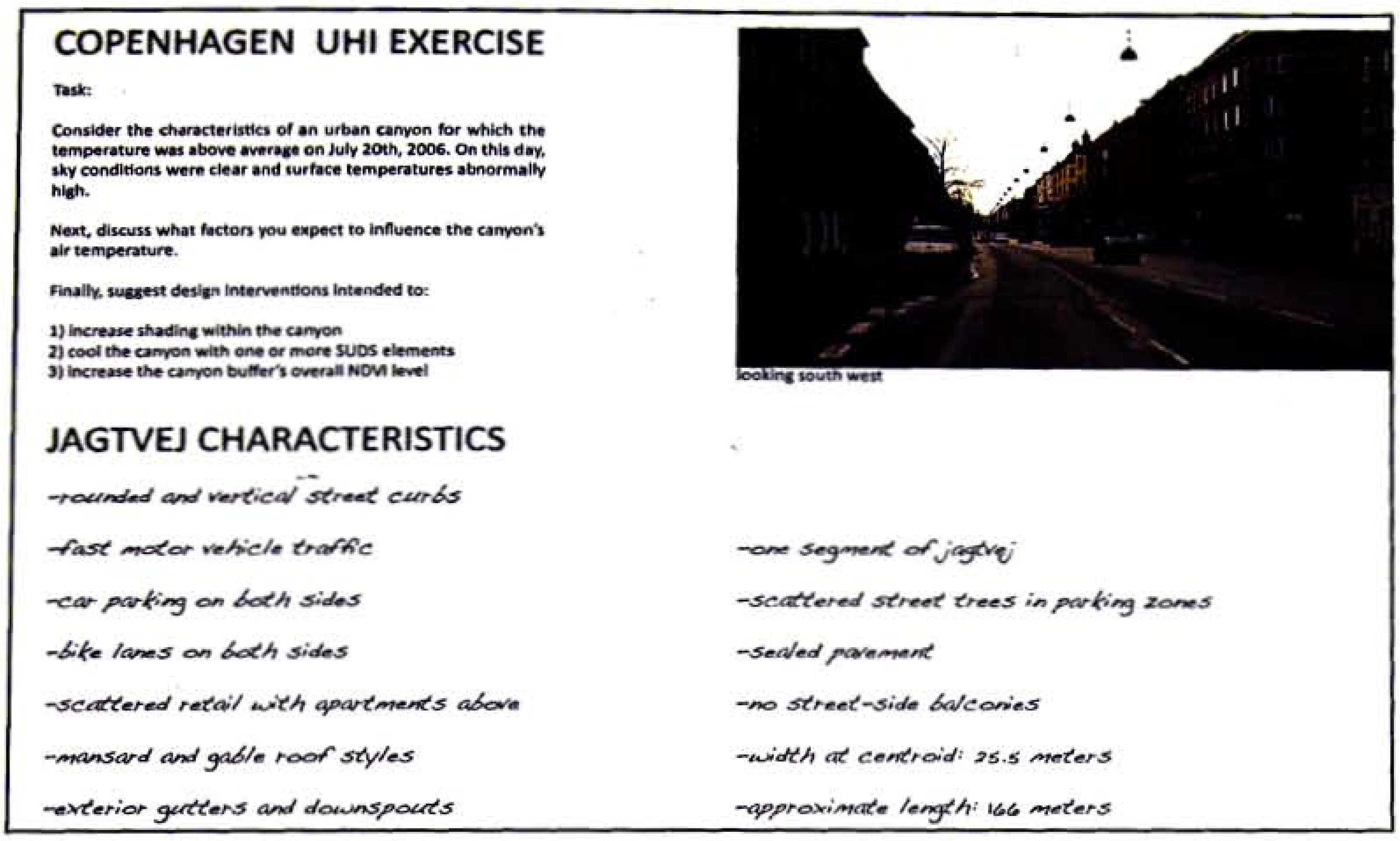
2186-2194). Researchers in Copenhagen could measure the cooling effect of an existing urban park on the urban fabric surrounding it using mobile data loggers mounted on bicycles. This information might be used in predictive studies regarding cooling expectations for new green infrastructure elements.

COMMUNICATION TOOLS

The herein described inquiry into the effects urban surface energy balance variables have on intra-urban air temperature variation of Copenhagen urban canyons and potential cooling responses was an iterative process conducted in the fall of 2011 and winter of 2012. At two points in the process, information gleaned was presented orally to representatives from the University of Copenhagen and the Copenhagen Municipality's Center for Parks and Nature. The first presentation was held in December of 2011 as a guest lecture to the graduate level course "Urban Ecosystems" within the Department of Forest and Landscape at the University of Copenhagen. The given lecture related preliminary findings with regard to the urban surface energy balance equation and was followed by a class exercise. For the class exercise, groups of students were given surface temperature, urban form, and Normalized Difference Vegetation Index information for three Copenhagen urban canyons. With the given information, included below, the students were asked to surmise potential green infrastructure interventions for the canyons as well as 150-meter buffer zones surrounding each canyon.

The second presentation was given in late January of 2012 to representatives from the University of Copenhagen and the Copenhagen Municipality's Center for Parks and Nature. The purpose of this presentation was to relay more advanced findings from the inquiry that might support the joint effort by the University of Copenhagen and the Copenhagen Municipality's Center for Parks and Nature to create a climate change adaptation plan for Copenhagen. As of March 2013, the creation of this plan is still in progress. In addition to the oral presentation, the slides from which appear below, a preliminary version of this report was delivered.

"Urban Ecosystems" Class Exercise, December 2011



COPENHAGEN UHI EXERCISE

Task:

Consider the characteristics of an urban canyon for which the temperature was above average on July 20th, 2006. On this day, sky conditions were clear and surface temperatures abnormally high.

Next, discuss what factors you expect to influence the canyon's air temperature.

Finally, suggest design interventions intended to:

1) increase shading within the canyon
2) cool the canyon with one or more SUDS elements
3) increase the canyon buffer's overall NDVI level

looking south west

JAGTVEJ CHARACTERISTICS

-rounded and vertical street curbs

-fast motor vehicle traffic

-car parking on both sides

-bike lanes on both sides

-scattered retail with apartments above

-mansard and gable roof styles

-exterior gutters and downspouts

-one segment of jagtvej

-scattered street trees in parking zones

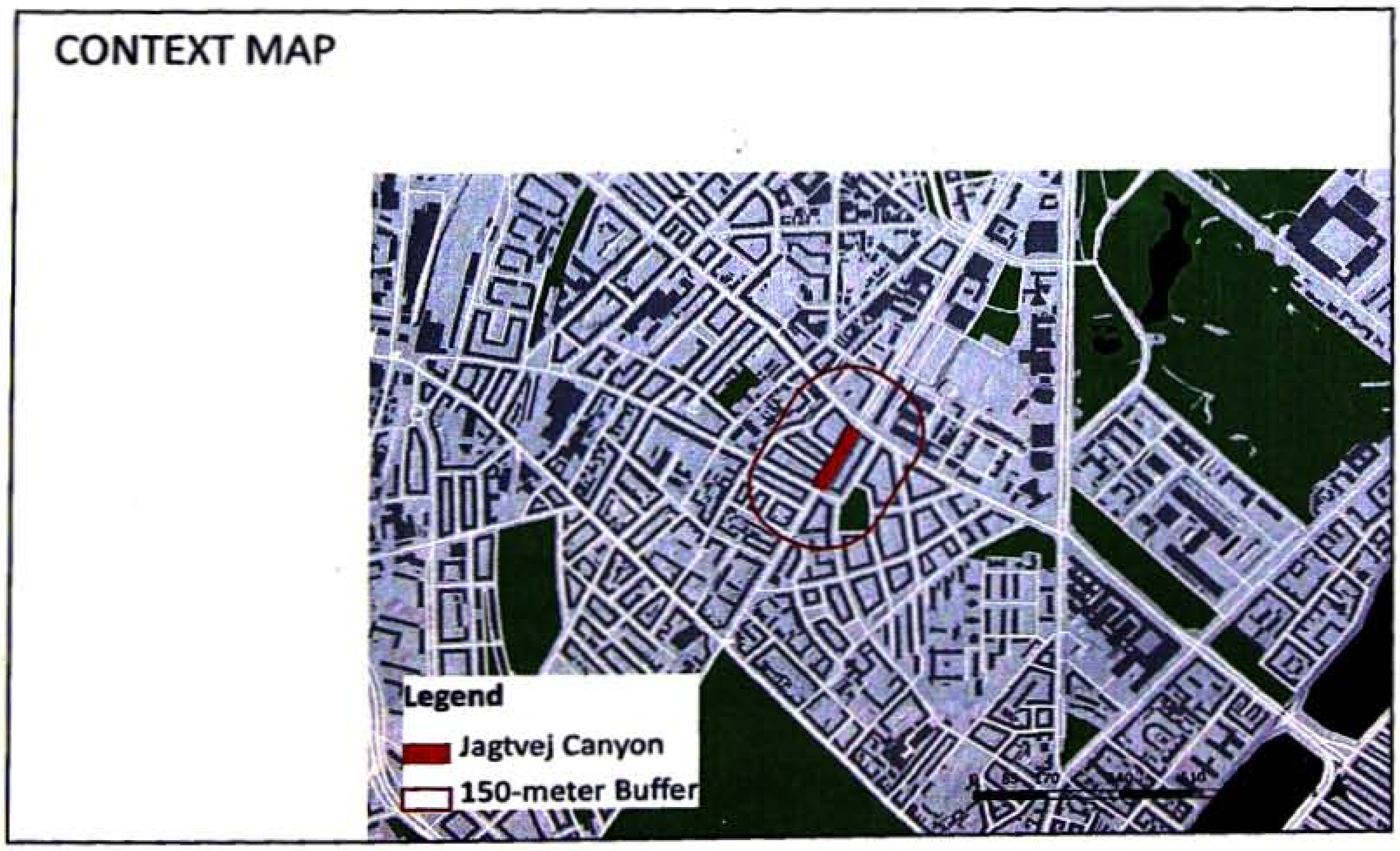
-sealed pavement

-no street-side balconies

-width at centroid: 25.5 meters

-approximate length: 166 meters

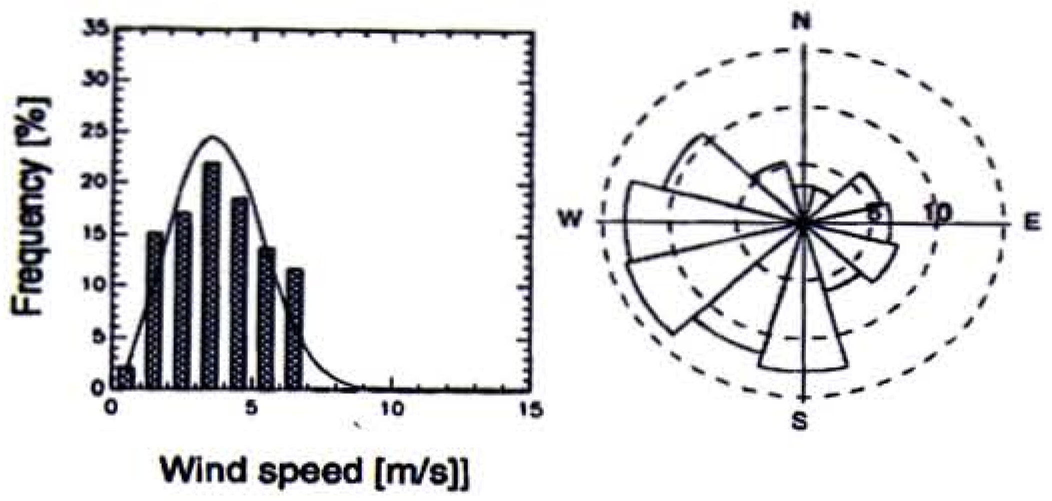
Jagtvej Urban Canyon Page One: Exercise instructions with Jagtvej urban form characteristics



CONTEXT MAP

Jagtvej Urban Canyon Page Two: Map showing Jagtvej with 150-meter buffer

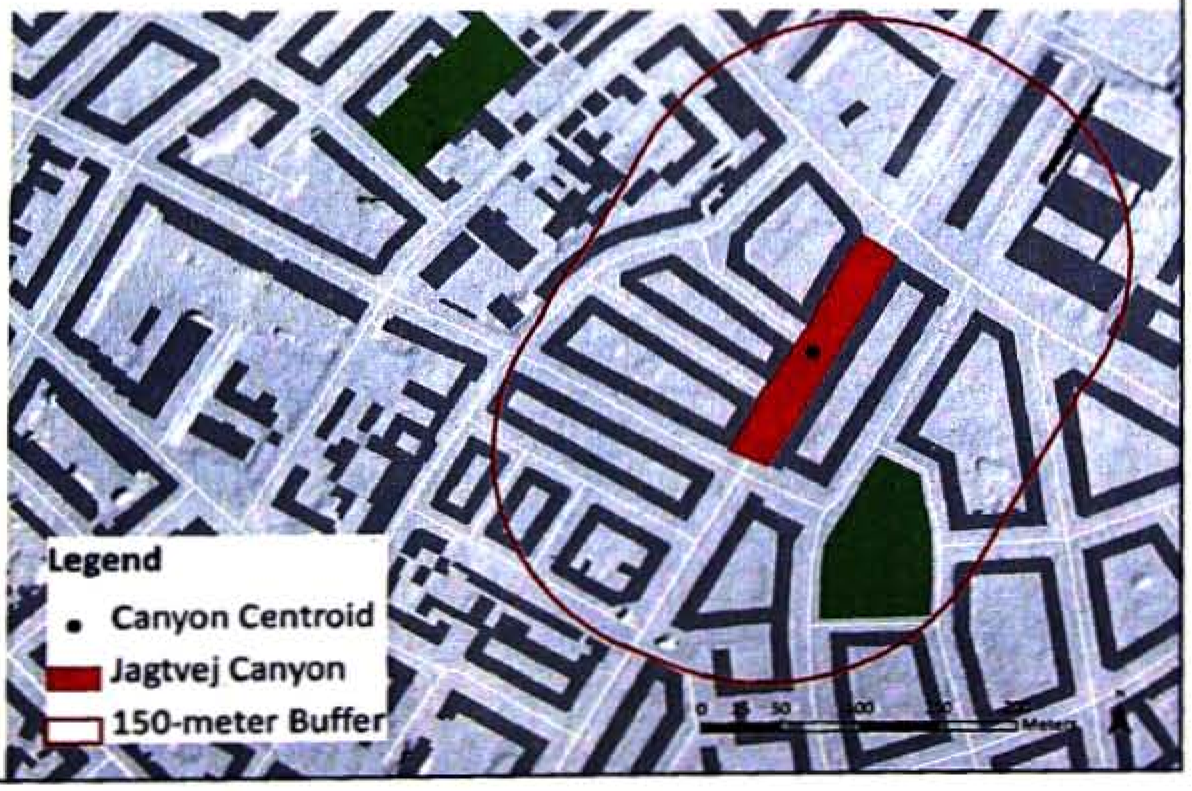
CANYON WIND ROSE AND HISTOGRAM



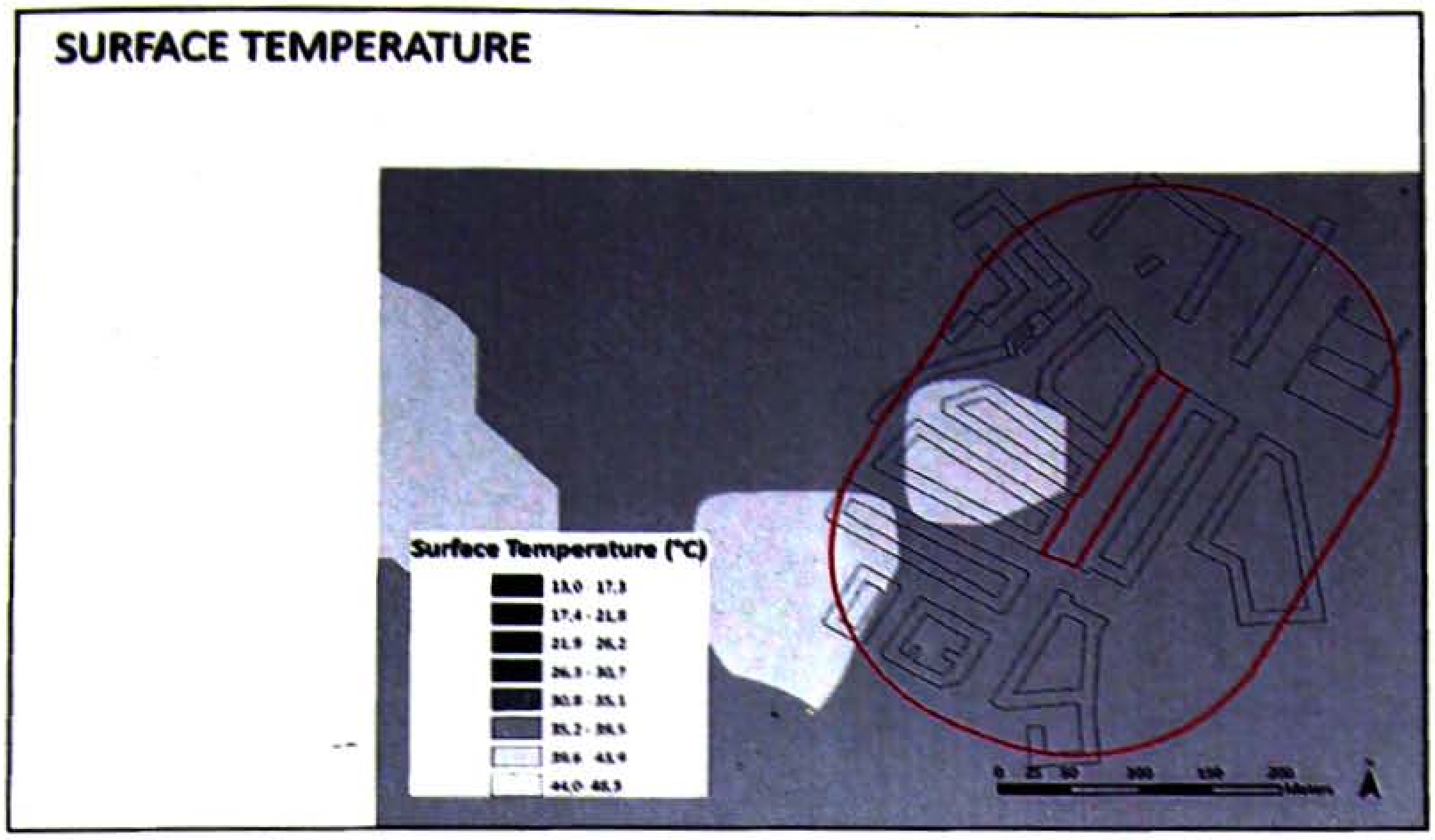
Source: Nielsen, M., 2000. Turbulent ventilation of a street canyon. Environmental Monitoring and Assessment 65, 396-398.

Jagtvej Urban Canyon Page Three: Wind rose and wind speed/frequency chart for the Jagtvej urban canyon

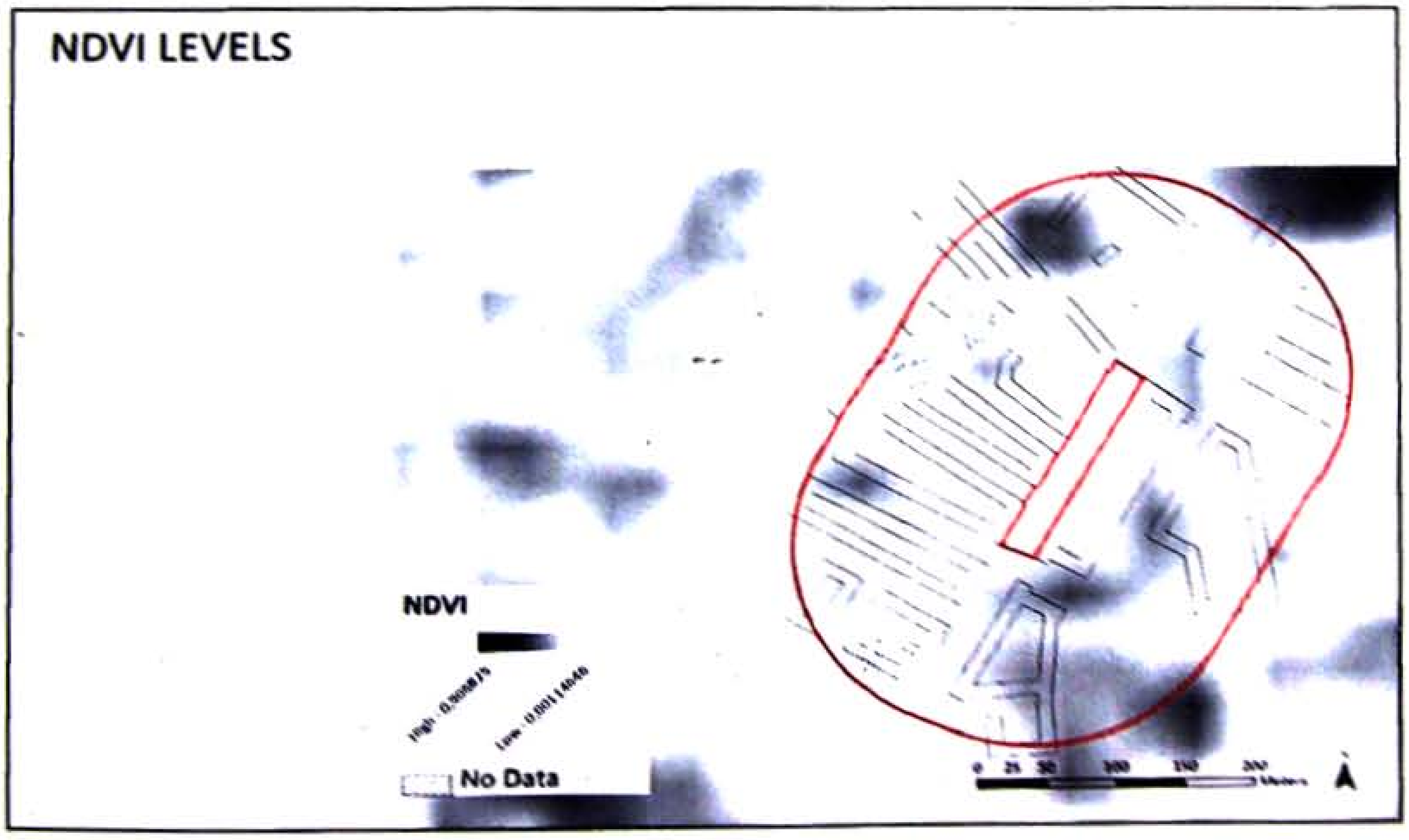
BASE MAP



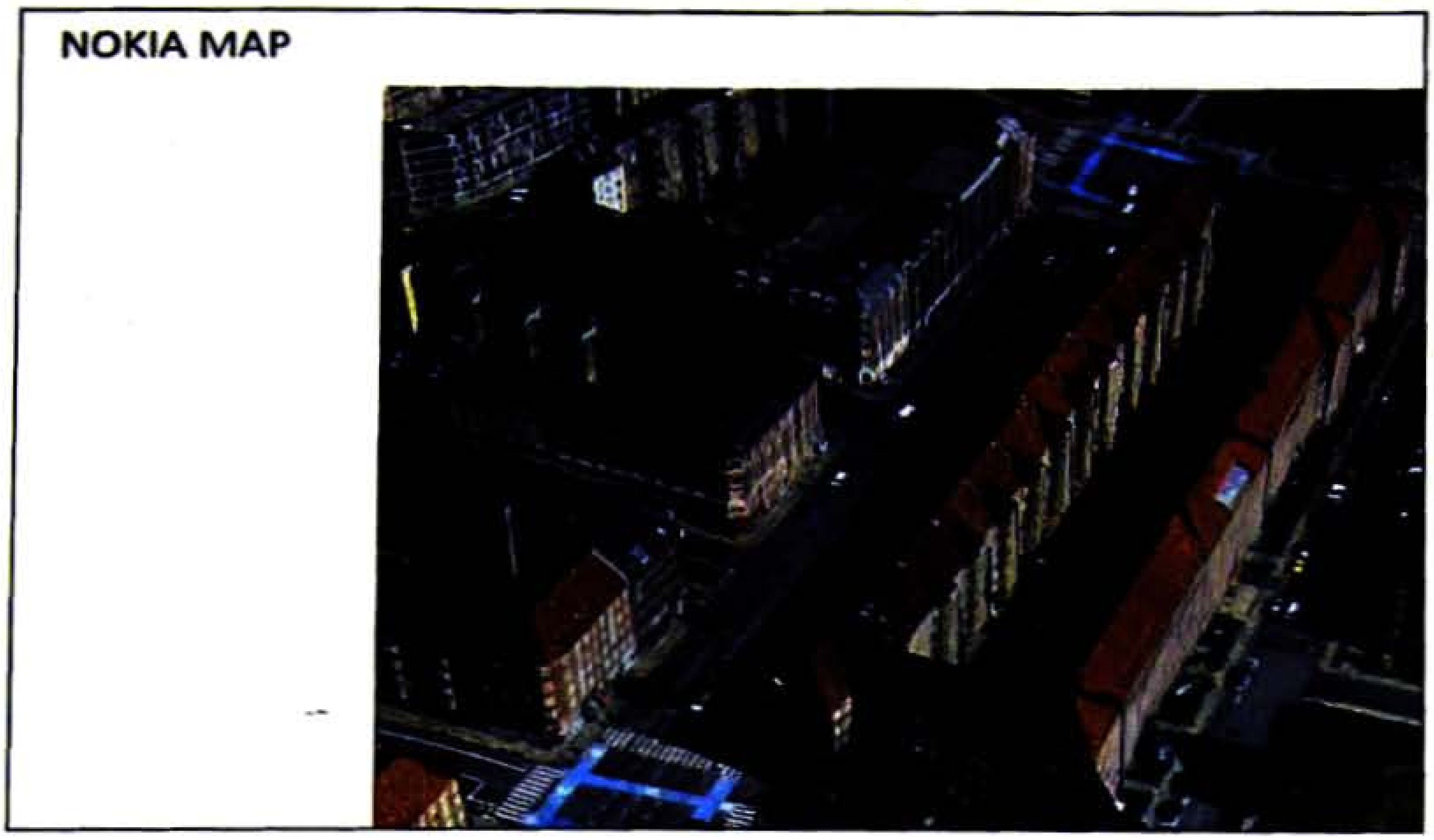
Jagtvej Urban Canyon Page Four: Map showing Jagtvej with 150-meter buffer and canyon centroid


SURFACE TEMPERATURE

Jagtvej Urban Canyon Page Five: Map showing Jagtvej with 150-meter buffer and surface temperature GIS data display

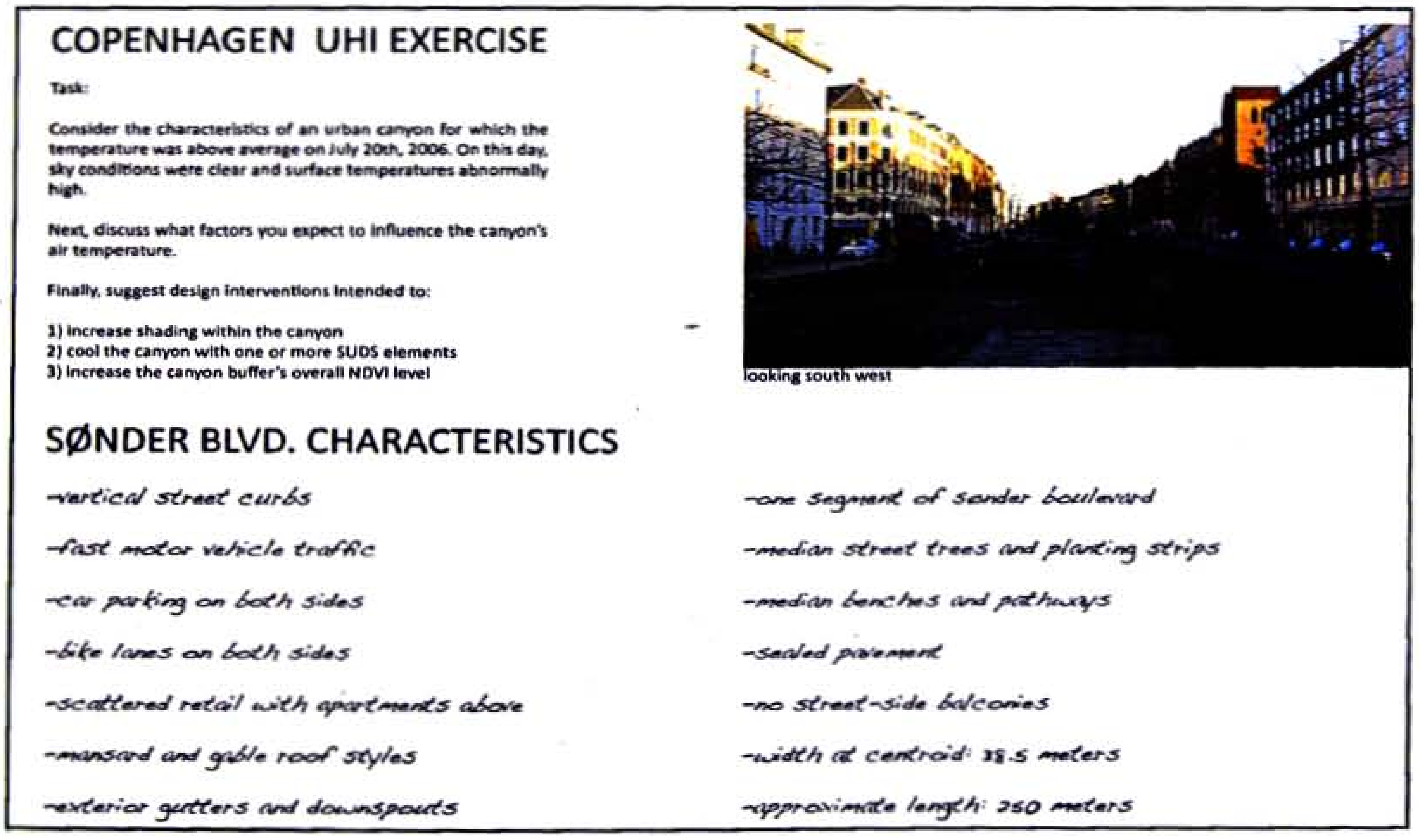

NDVI LEVELS

Jagtvej Urban Canyon Page Six: Map showing Jagtvej with 150-meter buffer and Normalized Difference Vegetation Index (NDVI) GIS data layer display



NOKIA MAP

Jagtvej Urban Canyon Page Seven: Map showing Jagtvej created on Nokia Maps website in December 2011



COPENHAGEN UHI EXERCISE

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1) increase shading within the canyon
2) cool the canyon with one or more SUDS elements
3) increase the canyon buffer's overall NDVI level

looking south west

SØNDER BLVD. CHARACTERISTICS

-vertical street curbs

-fast motor vehicle traffic

-car parking on both sides

-bike lanes on both sides

-scattered retail with apartments above

-mansard and gable roof styles

-exterior gutters and downspouts

-one segment of Sønder boulevard

-median street trees and planting strips

-median benches and pathways

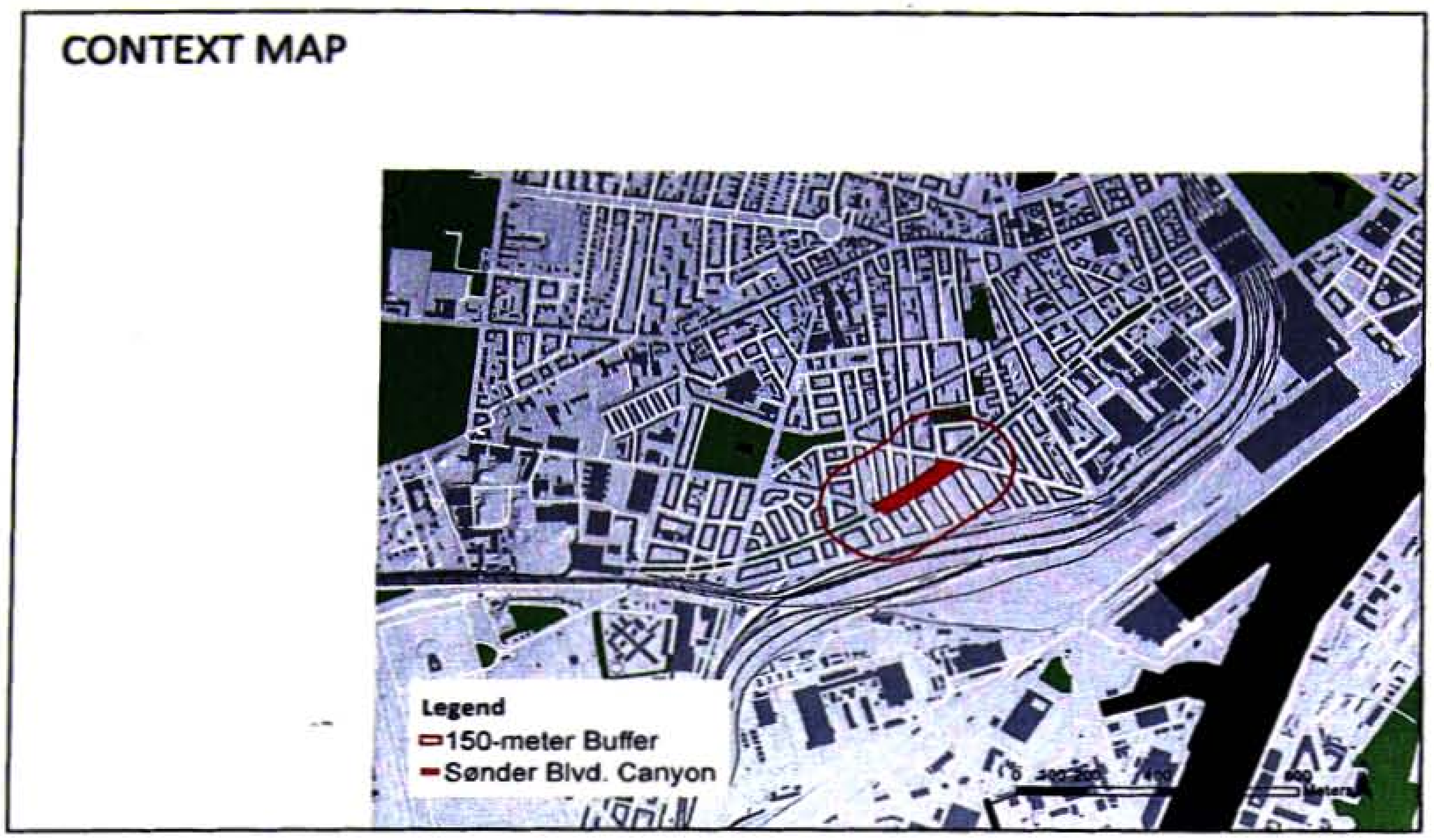
-sealed pavement

-no street-side balconies

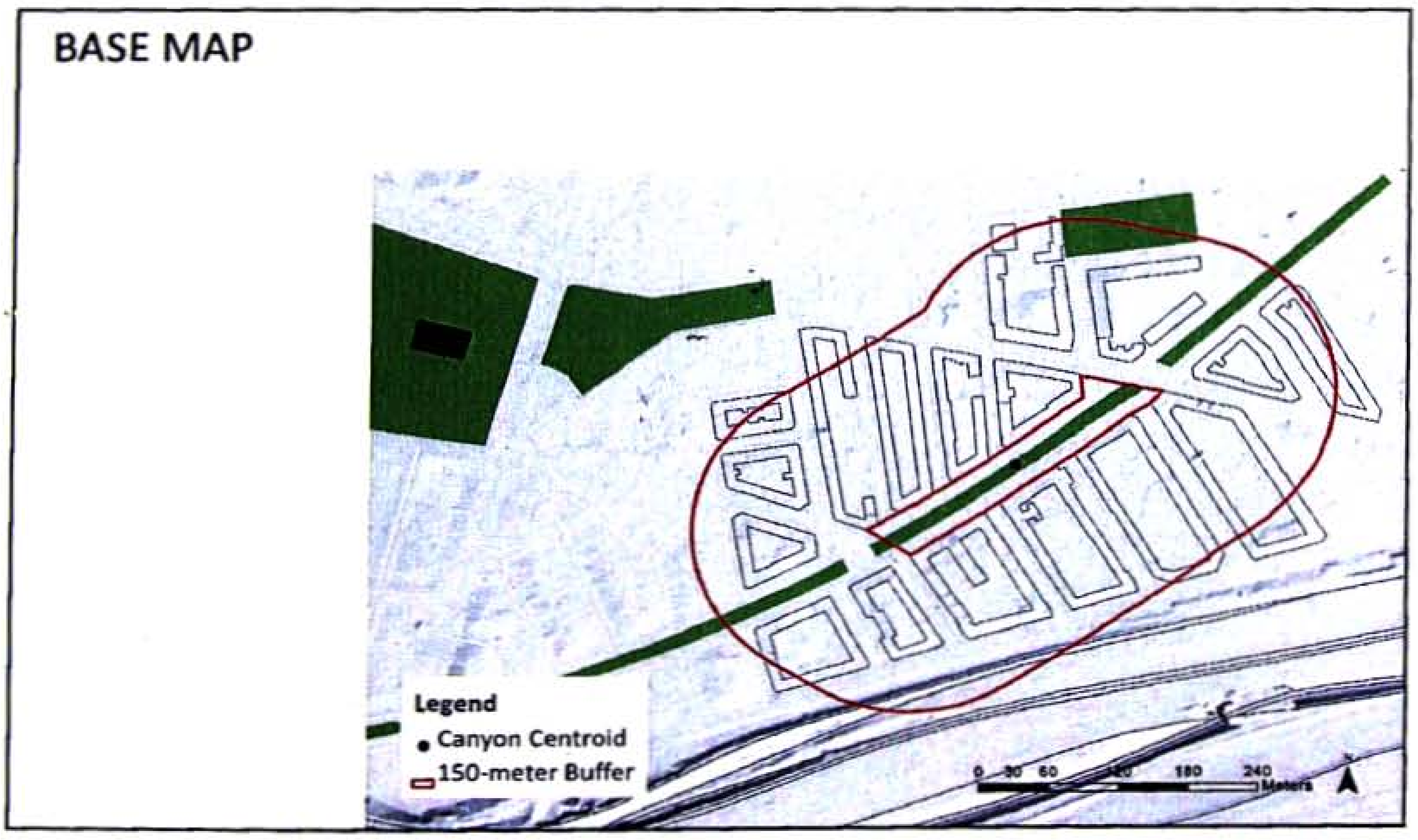
-width at centroid: 38.5 meters

-approximate length: 250 meters

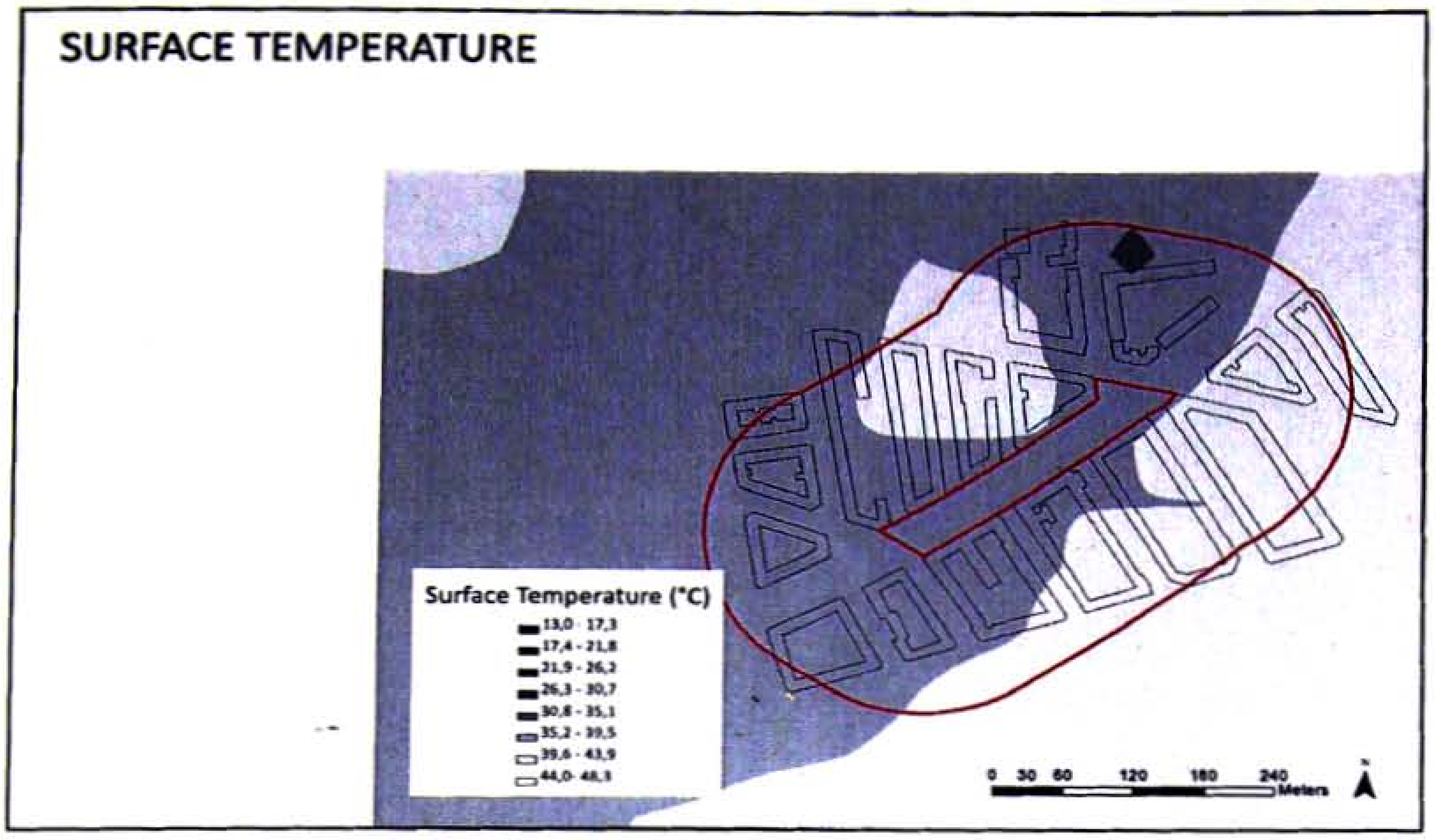
Sønder Boulevard Urban Canyon Page One: Exercise instructions with Sønder Boulevard urban form characteristics



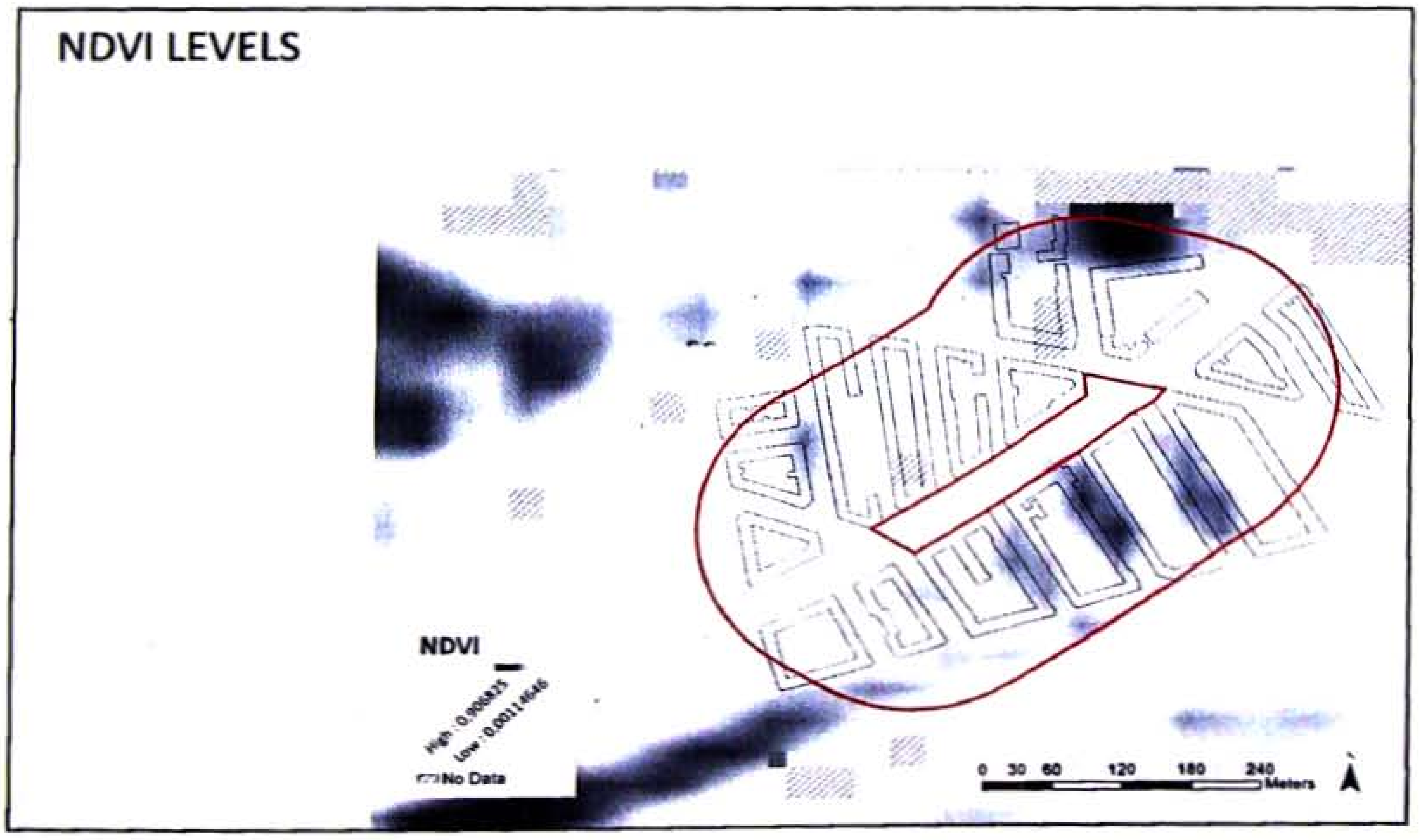
Sønder Boulevard Urban Canyon Page Two: Map showing Sønder Boulevard with 150-meter buffer



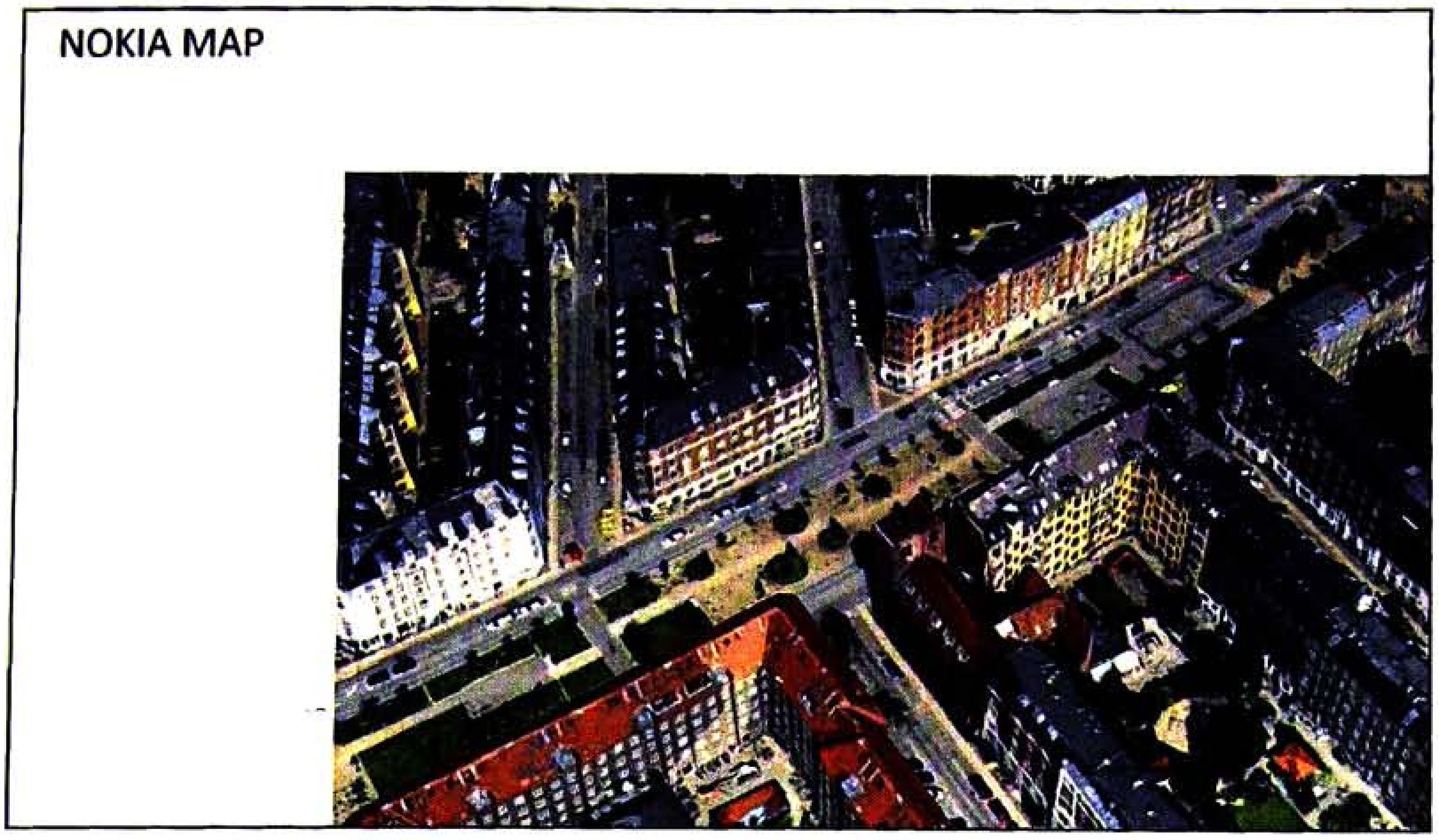
Sønder Boulevard Urban Canyon Page Three: Map showing Sønder Boulevard with 150-meter buffer and canyon centroid



Sønder Boulevard Urban Canyon Page Four: Map showing Sønder Boulevard with 150-meter buffer and surface temperature GIS data display

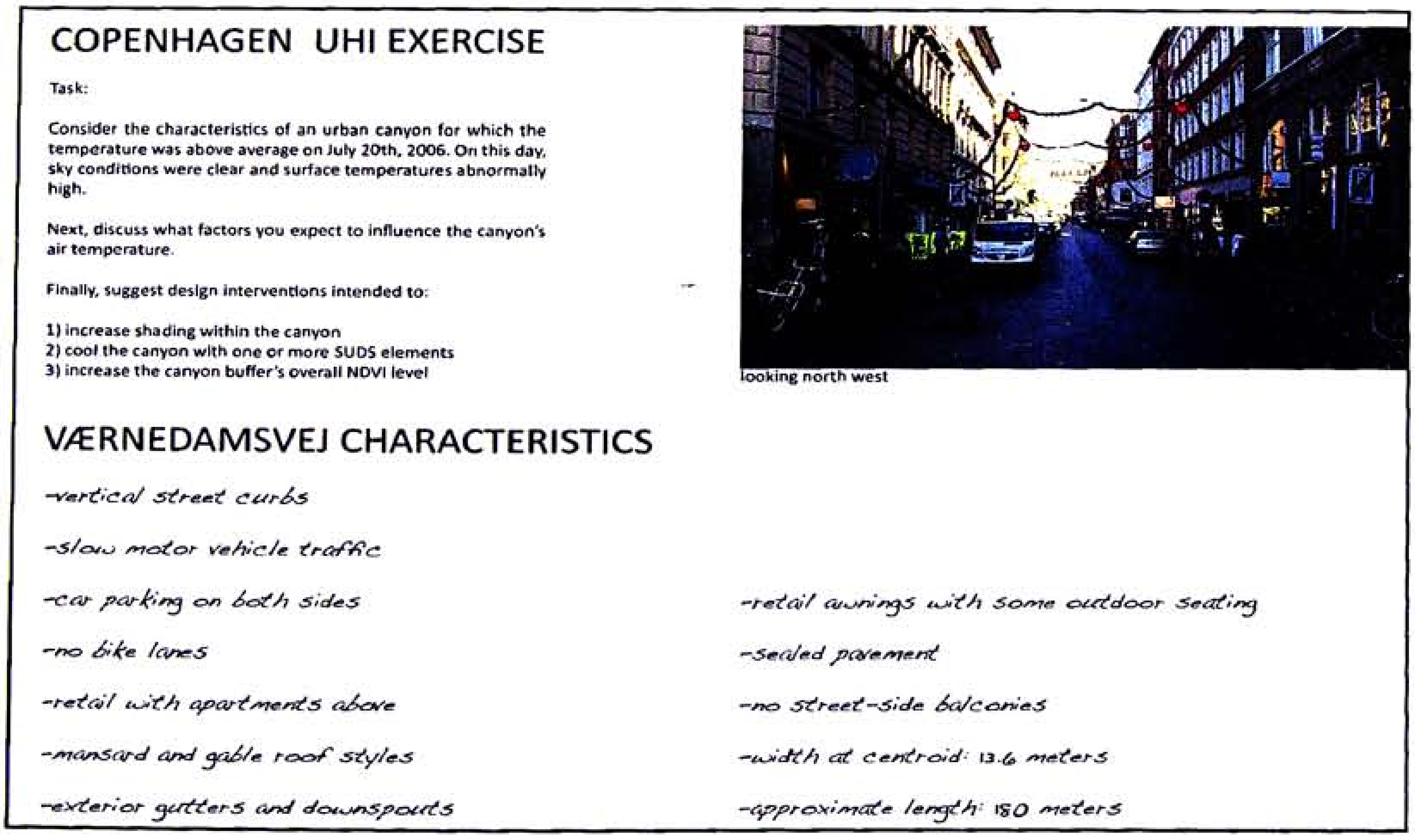


Sønder Boulevard Urban Canyon Page Six: Map showing Sønder Boulevard with 150-meter buffer and Normalized Difference Vegetation Index (NDVI) GIS data layer display



NOKIA MAP

Sønder Boulevard Urban Canyon Page Seven: Map showing Sønder Boulevard created on Nokia Maps website in December 2011



COPENHAGEN UHI EXERCISE

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1) increase shading within the canyon
2) cool the canyon with one or more SUDS elements
3) increase the canyon buffer's overall NDVI level

looking north west

VÆRNEDAMSVEJ CHARACTERISTICS

-vertical street curbs

-slow motor vehicle traffic

-car parking on both sides

-no bike lanes

-retail with apartments above

-mansard and gable roof styles

-exterior gutters and downspouts

-retail awnings with some outdoor seating

-sealed pavement

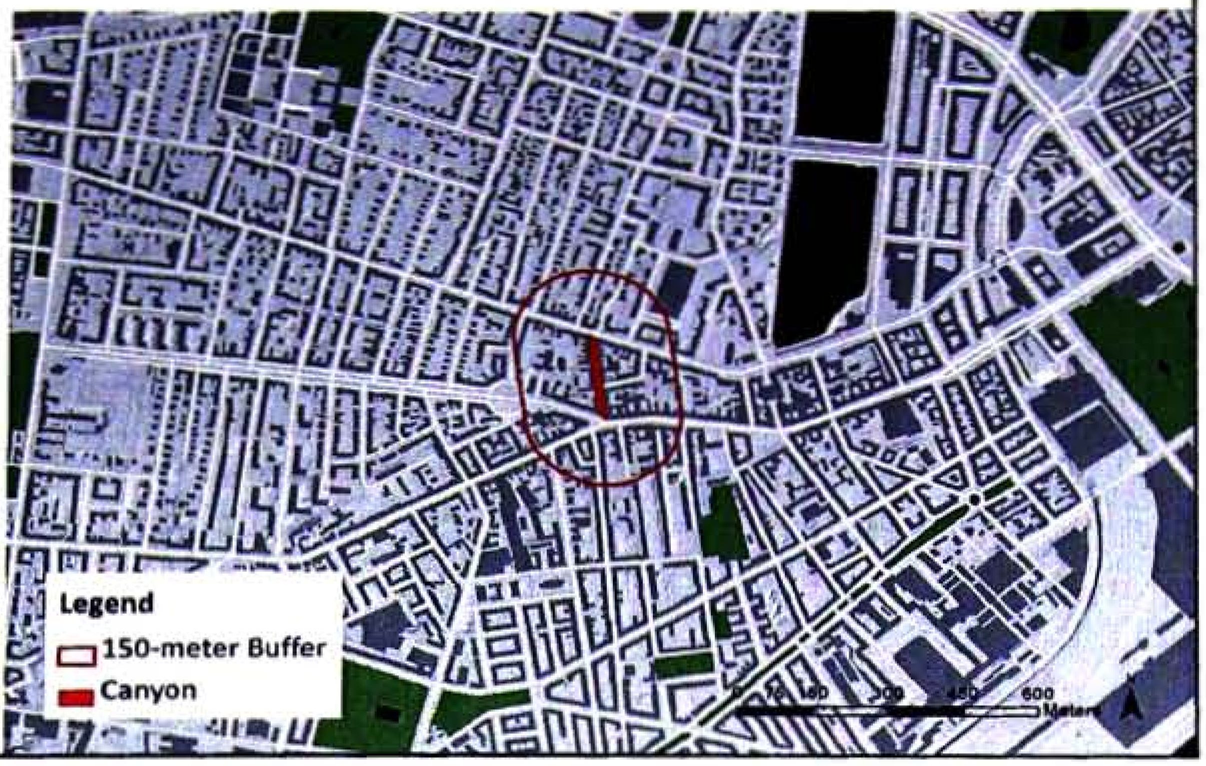
-no street-side balconies

-width at centroid: 13.6 meters

-approximate length: 180 meters

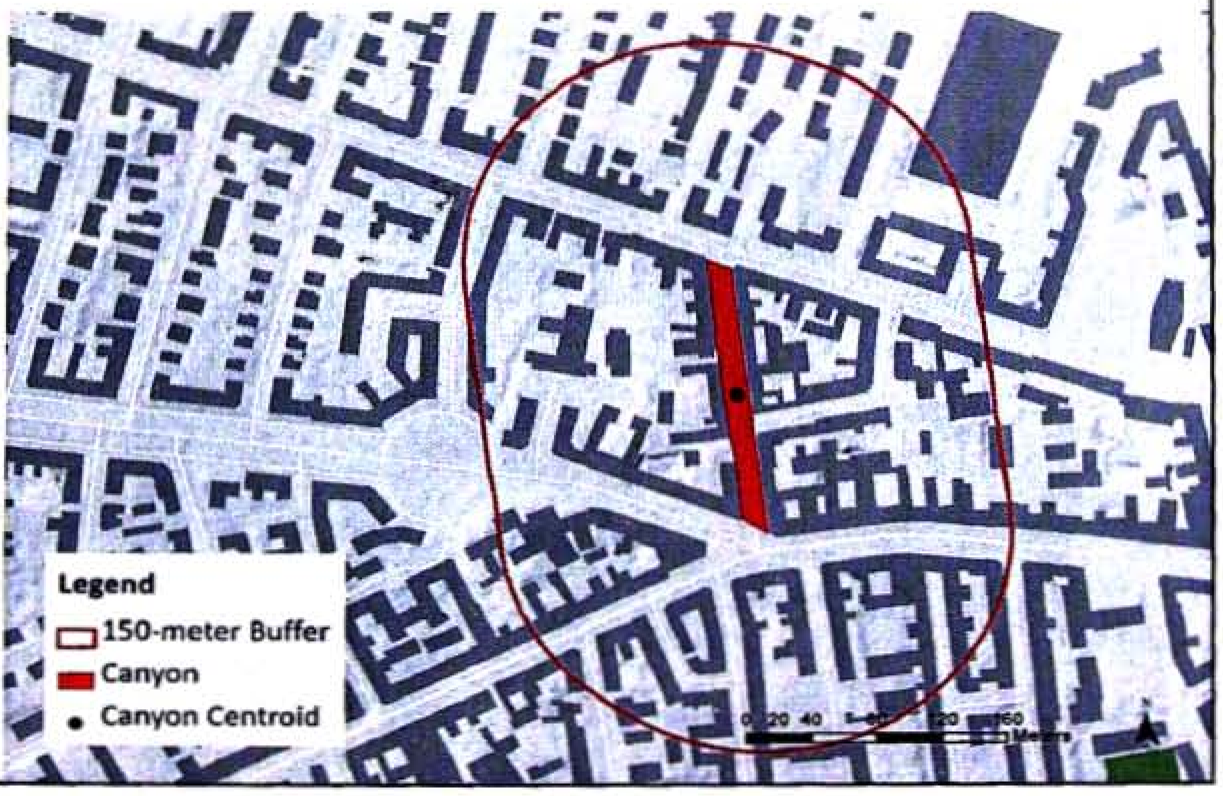
Værnedamsvej Urban Canyon Page One: Exercise instructions with Værnedamsvej urban form characteristics

CONTEXT MAP

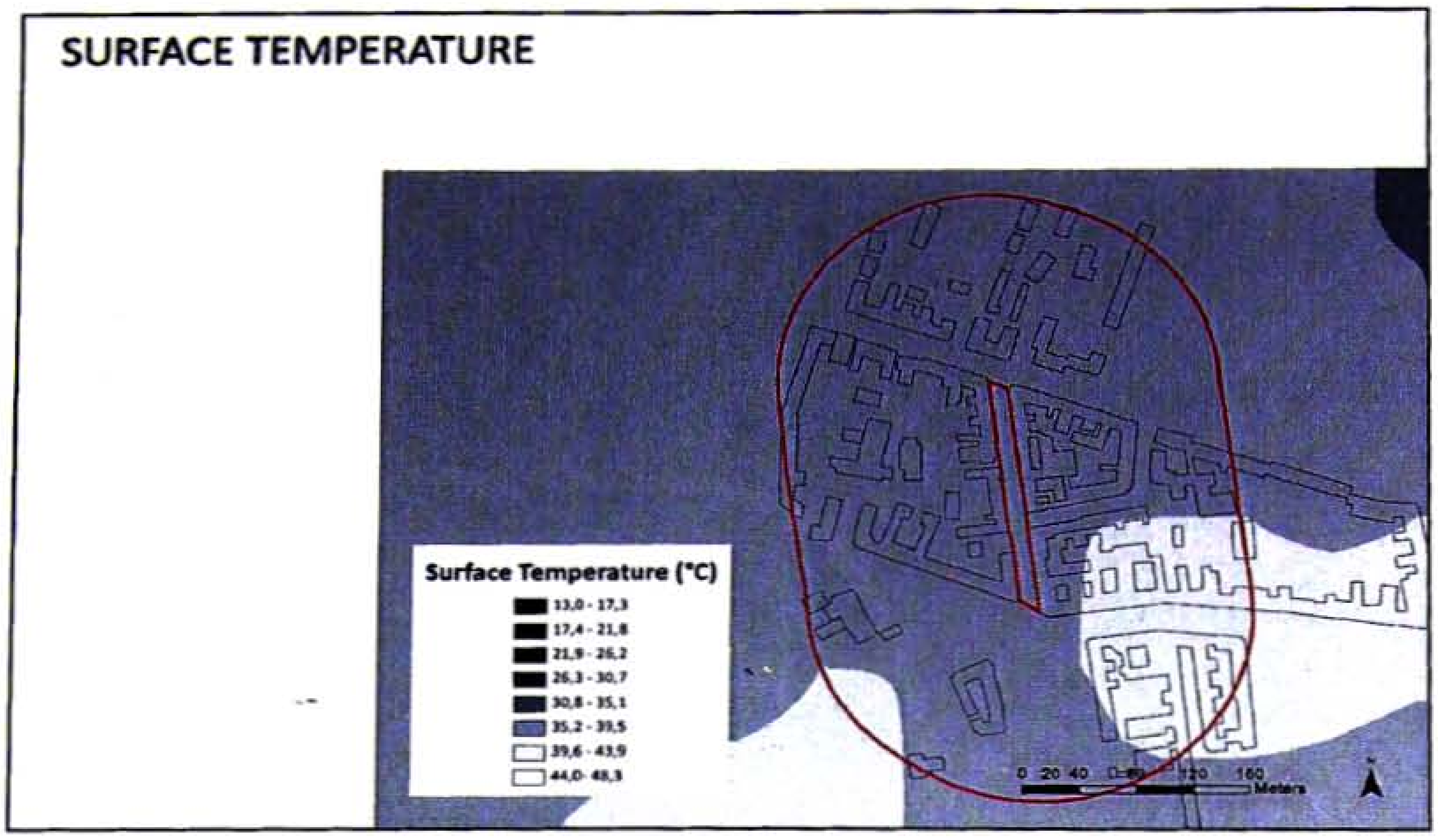


Værnedamsvej Urban Canyon Page Two: Map showing Værnedamsvej with 150-meter buffer

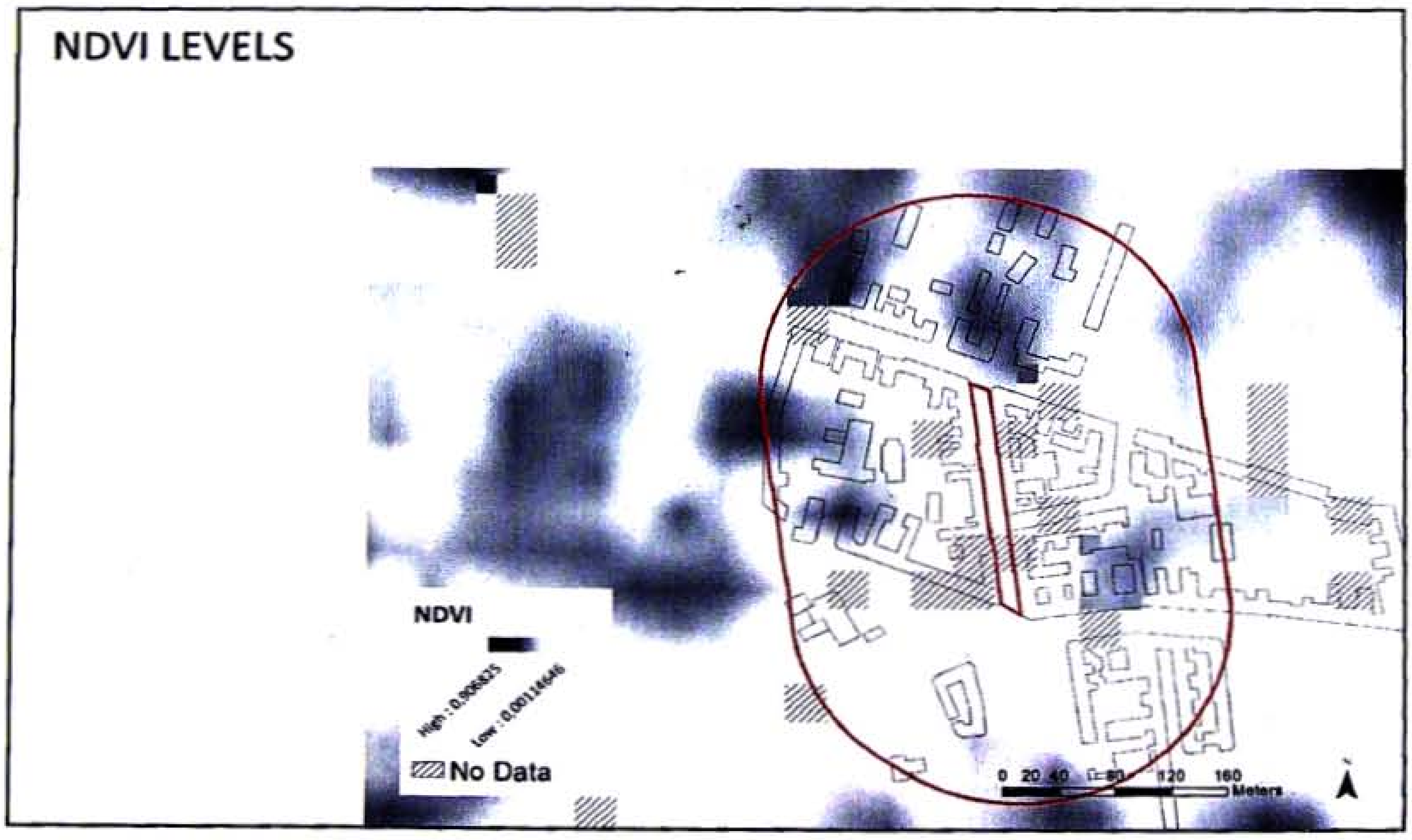
BASE MAP



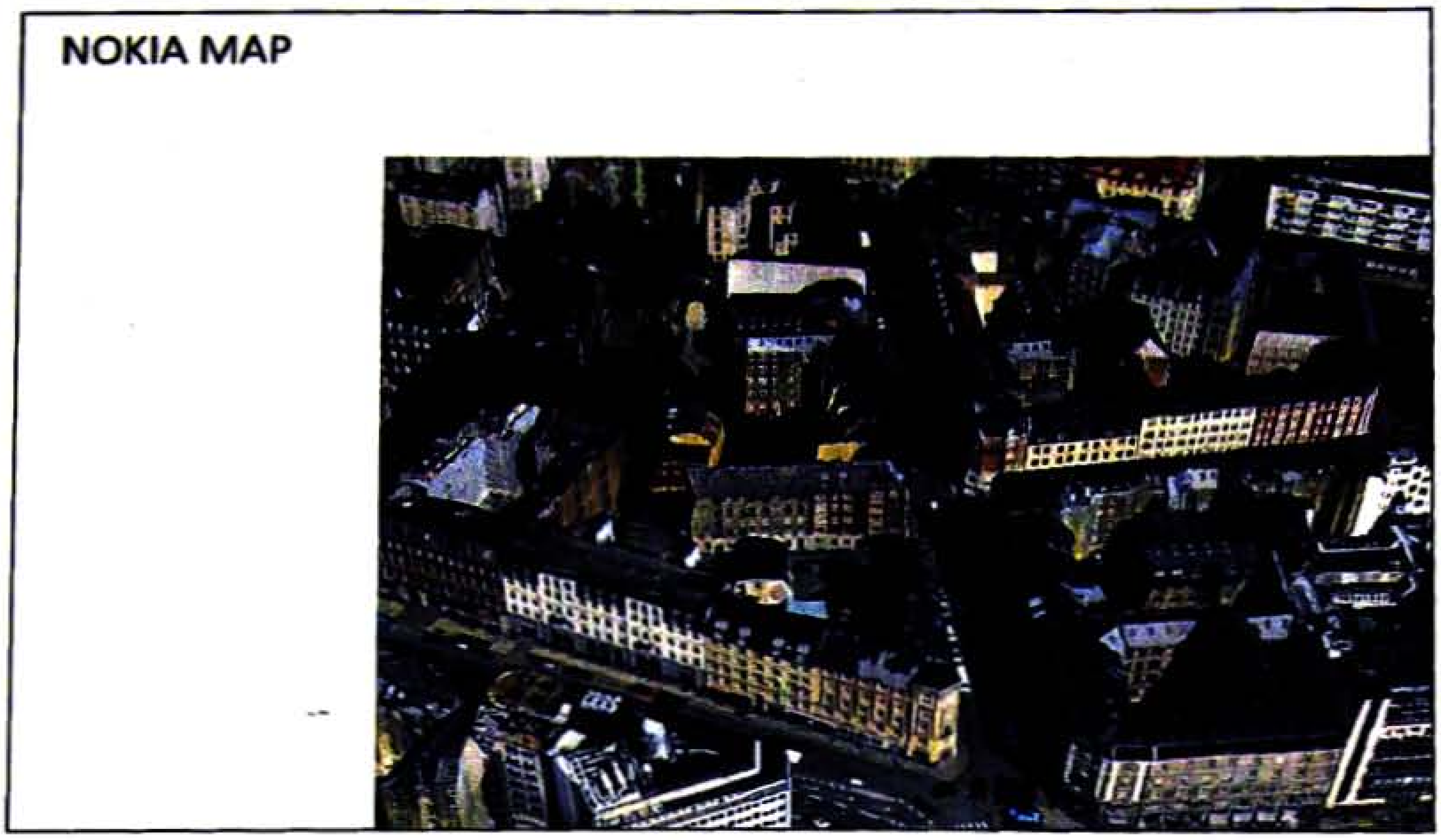
Værnedamsvej Urban Canyon Page Three: Map showing Værnedamsvej with 150-meter buffer and canyon centroid



Værnedamsvej Urban Canyon Page Four: Map showing Værnedamsvej with 150-meter buffer and surface temperature GIS data display



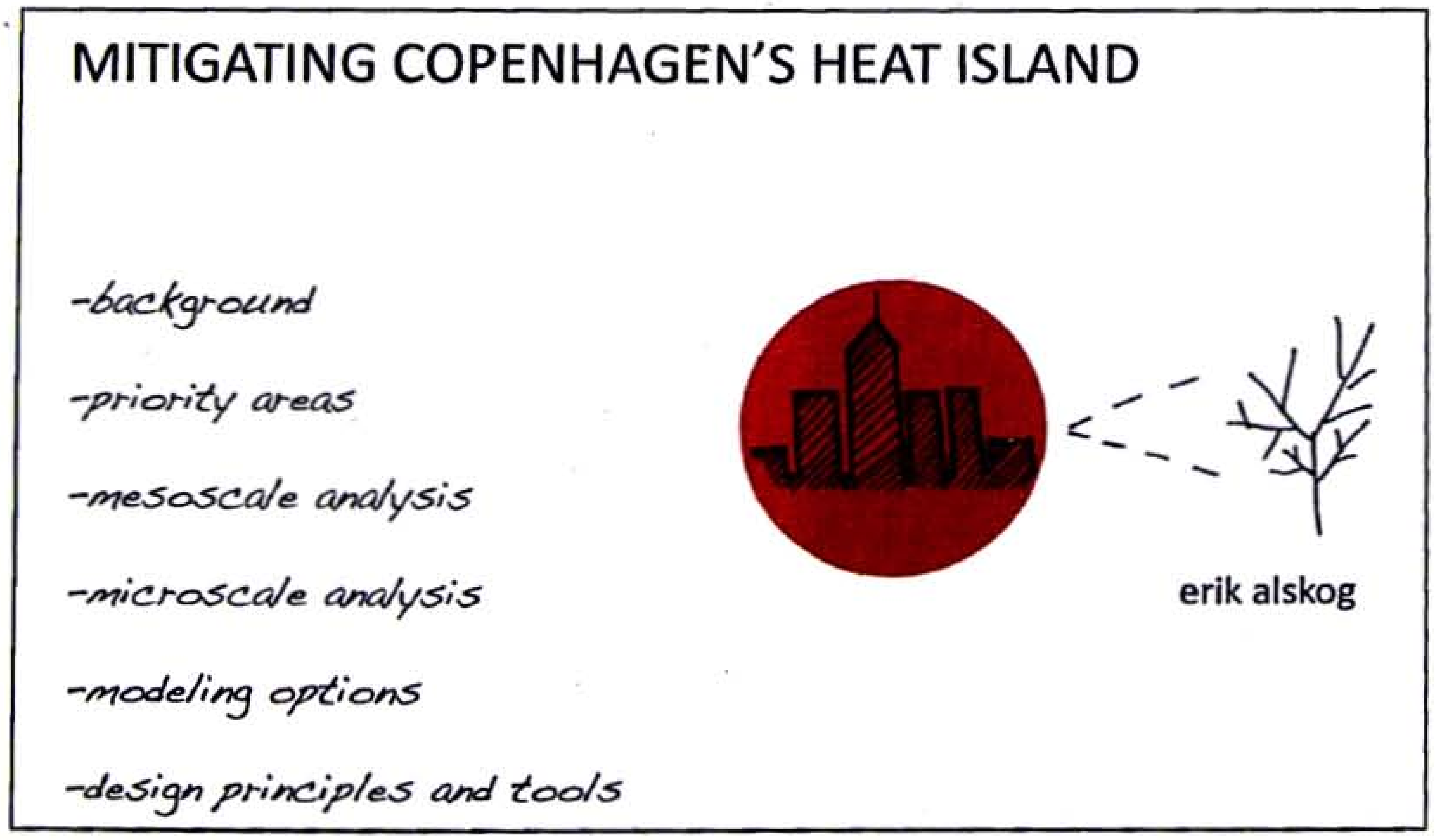
Værnedamsvej Urban Canyon Page Six: Map showing Værnedamsvej with 150-meter buffer and Normalized Difference Vegetation Index (NDVI) GIS data layer display



NOKIA MAP

Værnedamsvej Urban Canyon Page Seven: Map showing Værnedamsvej created on Nokia Maps website in December 2011

Presentation To University of Copenhagen and the Copenhagen Municipality's Center for Parks and Nature, January 2012



MITIGATING COPENHAGEN'S HEAT ISLAND

-background

-priority areas

-mesoscale analysis

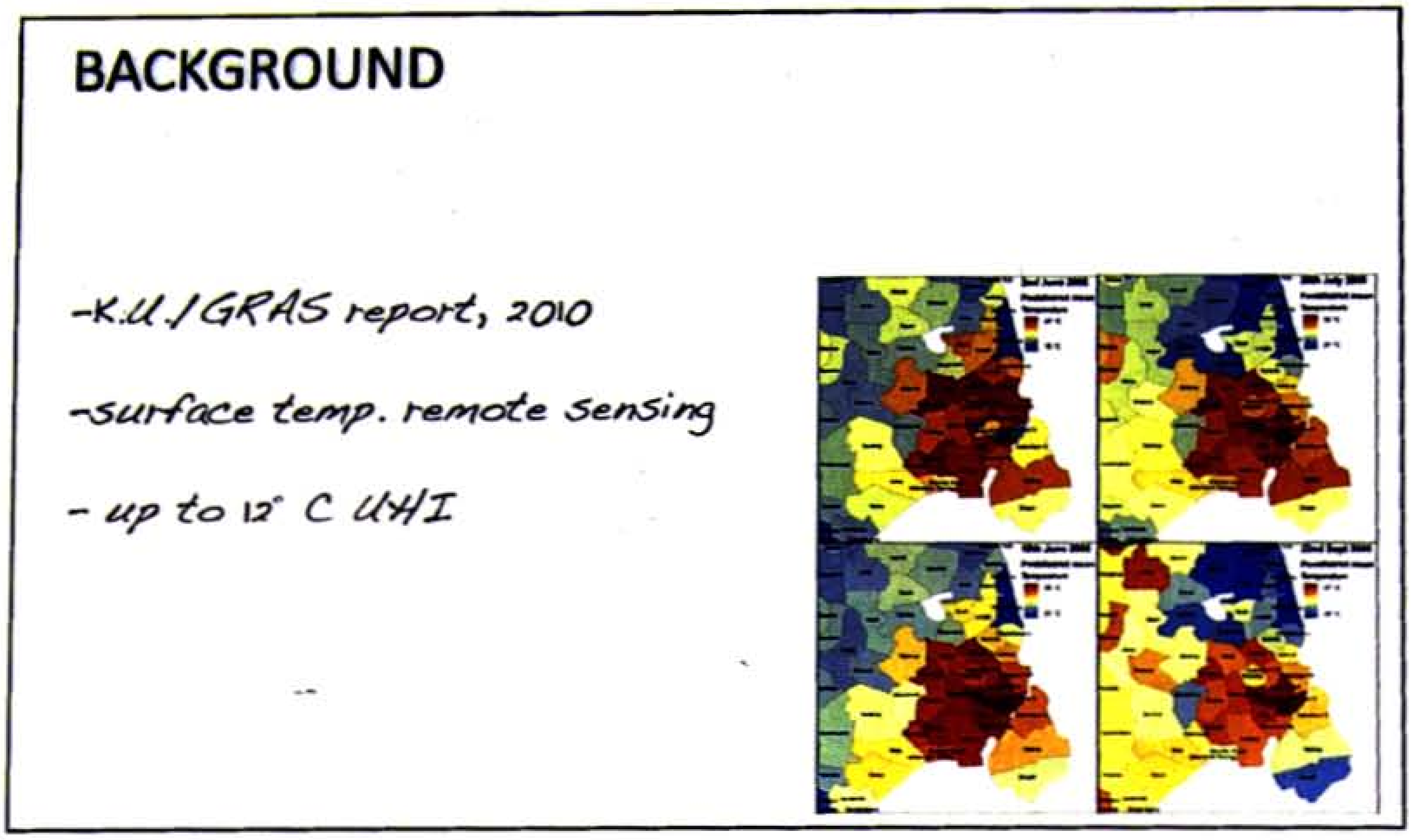
-microscale analysis

-modeling options

-design principles and tools

erik alskog

Slide One: Introduction slide with list of topics to be discussed



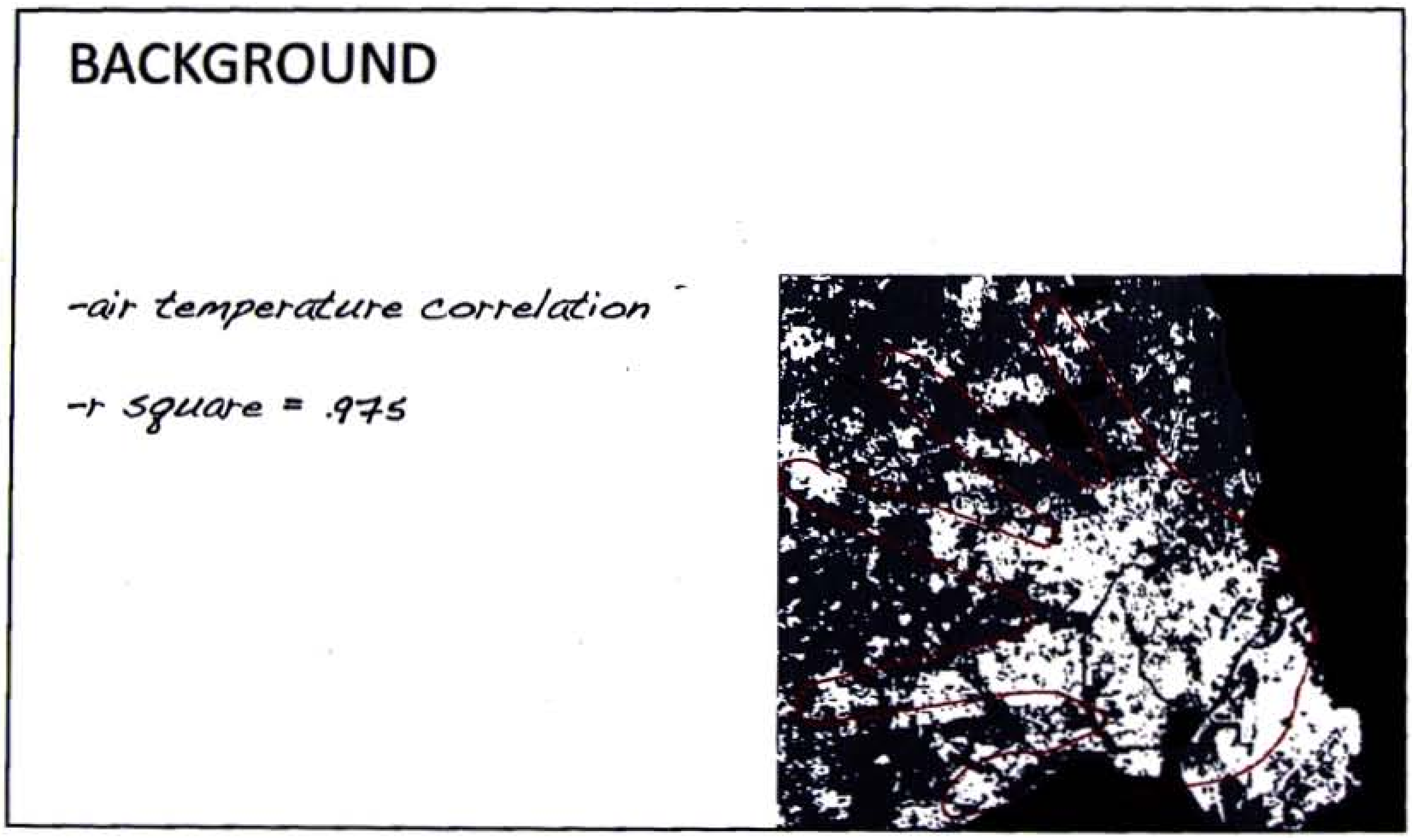
BACKGROUND

-K.U./GRAS report, 2010

-surface temp. remote sensing

- up to 12° C UHI

Slide Two: Background urban heat island (UHI) information gleaned from 2010 University of Copenhagen unpublished report

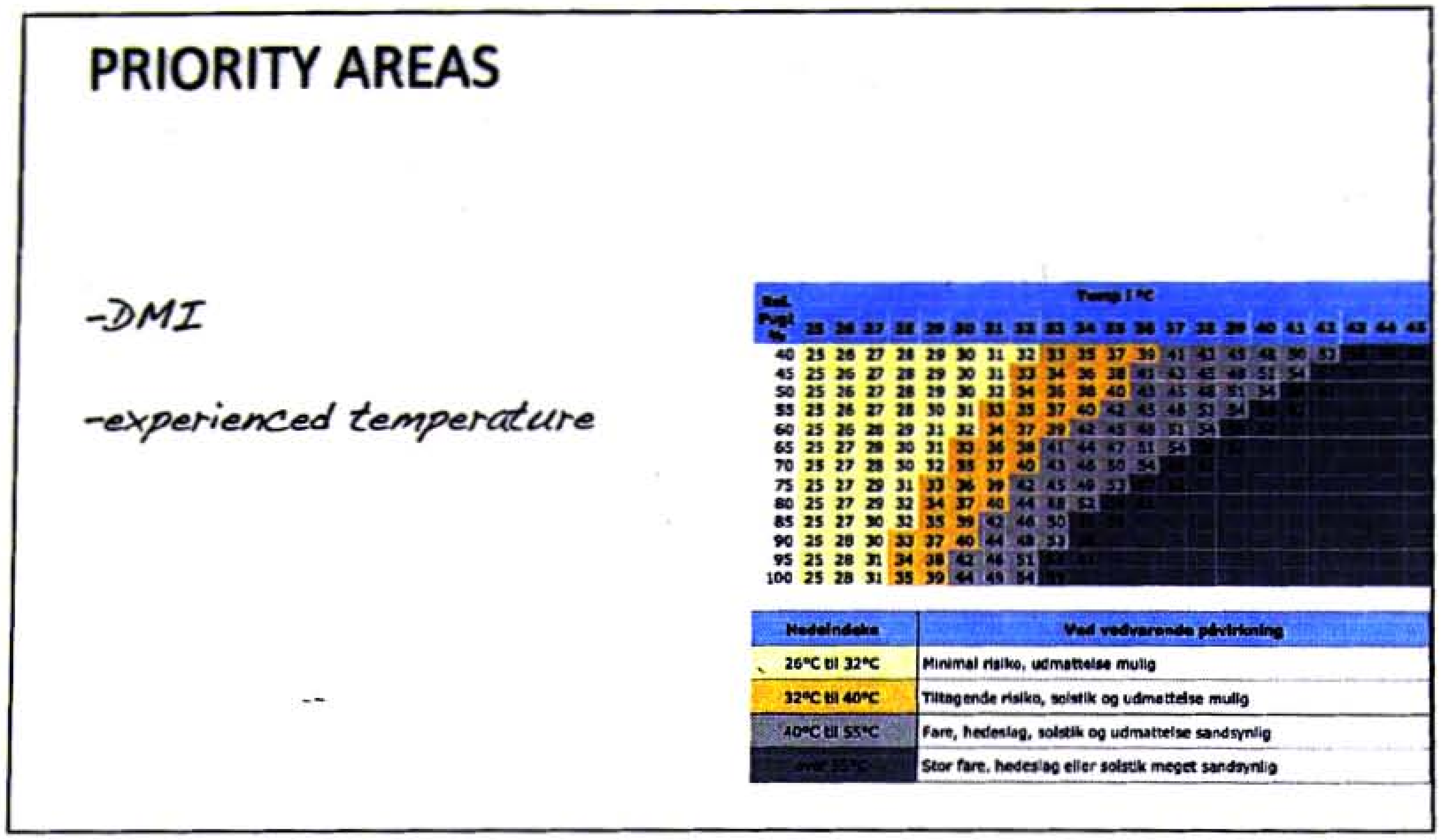


BACKGROUND

-air temperature correlation

-r square = .975

Slide Three: Explanation of linear relationship between surface and air temperatures within Copenhagen based on statistical analysis included in the 2010 University of Copenhagen report



PRIORITY AREAS

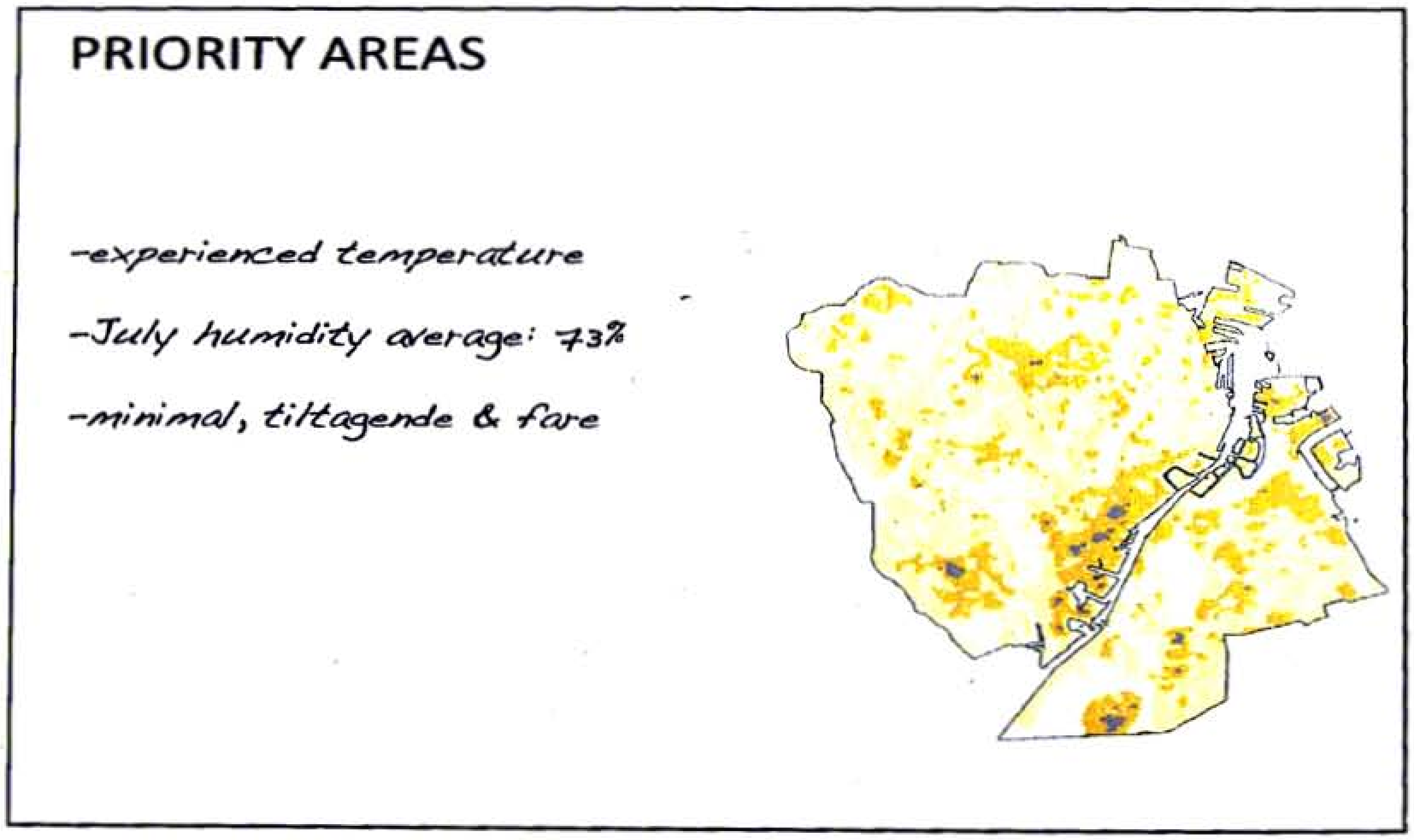
-DMI

-experienced temperature

Rel. Fugt %	Temp i °C																				
	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
40	25	26	27	28	29	30	31	32	33	35	37	39	41	43	45	48	50	53			
45	25	26	27	28	29	30	31	33	34	36	38	41	43	45	48	51	54				
50	25	26	27	28	29	30	32	34	36	38	40	43	45	48	51	54					
55	25	26	27	28	30	31	33	35	37	40	42	45	48	51	54						
60	25	26	28	29	31	32	34	37	39	42	45	48	51	54							
65	25	27	28	30	31	33	36	38	41	44	47	51	54								
70	25	27	28	30	32	35	37	40	43	46	50	54									
75	25	27	29	31	33	36	39	42	45	49	53										
80	25	27	29	32	34	37	40	44	48	52											
85	25	27	30	32	35	39	42	46	50												
90	25	28	30	33	37	40	44	48	53												
95	25	28	31	34	38	42	46	51													
100	25	28	31	35	39	44	49	54													

Hedeindeks	Ved vedvarende påvirkning
26°C til 32°C	Minimal risiko, udmattelse mulig
32°C til 40°C	Tiltagende risiko, solstik og udmattelse mulig
40°C til 55°C	Fare, hedeslag, solstik og udmattelse sandsynlig
over 55°C	Stor fare, hedeslag eller solstik meget sandsynlig

Slide Four: Discussion of heat wave danger within Copenhagen based on data from the Danish Meteorological Institute (DMI) included in the 2010 University of Copenhagen report



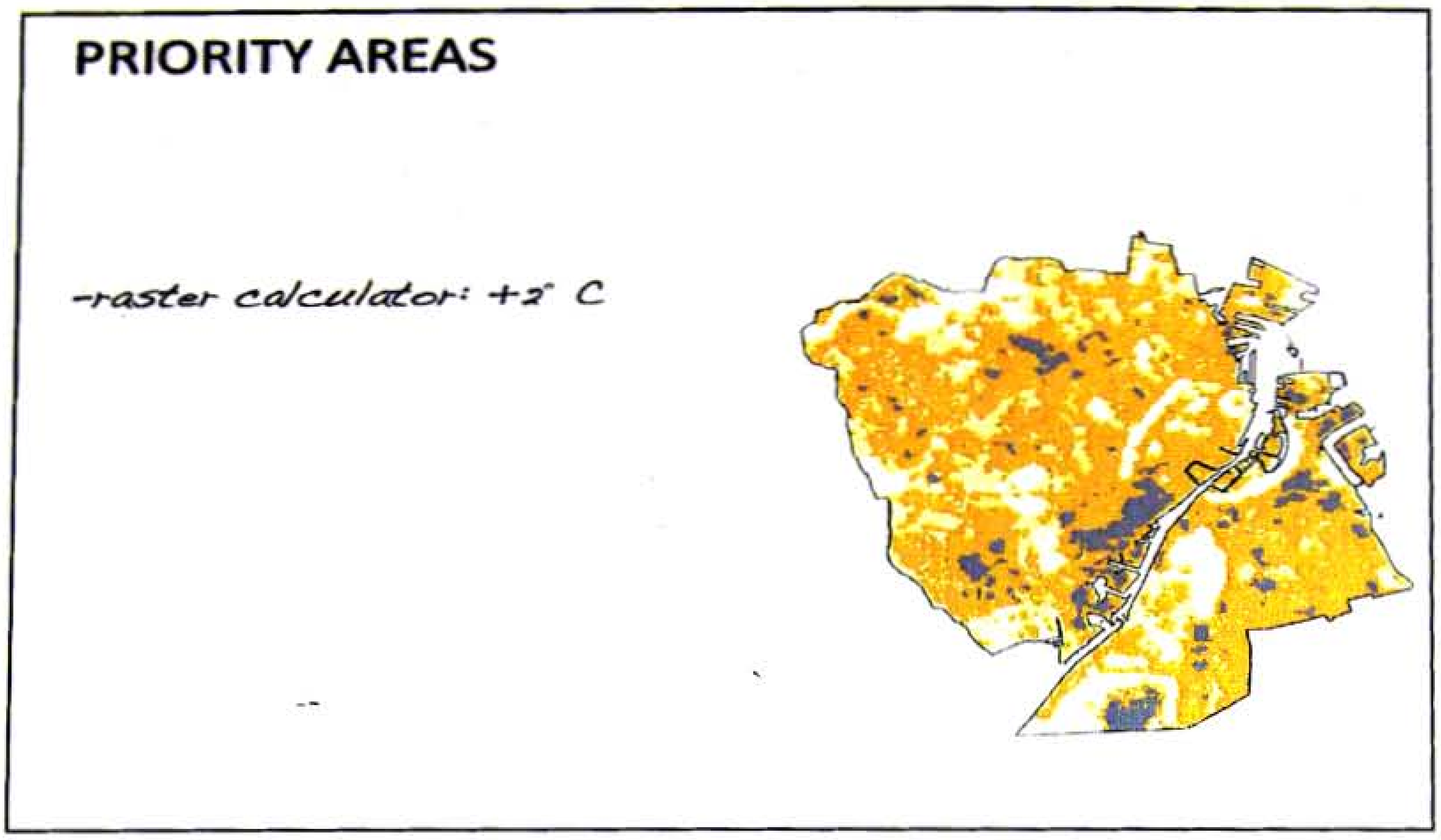
PRIORITY AREAS

-experienced temperature

-July humidity average: 73%

-minimal, tiltagende & fare

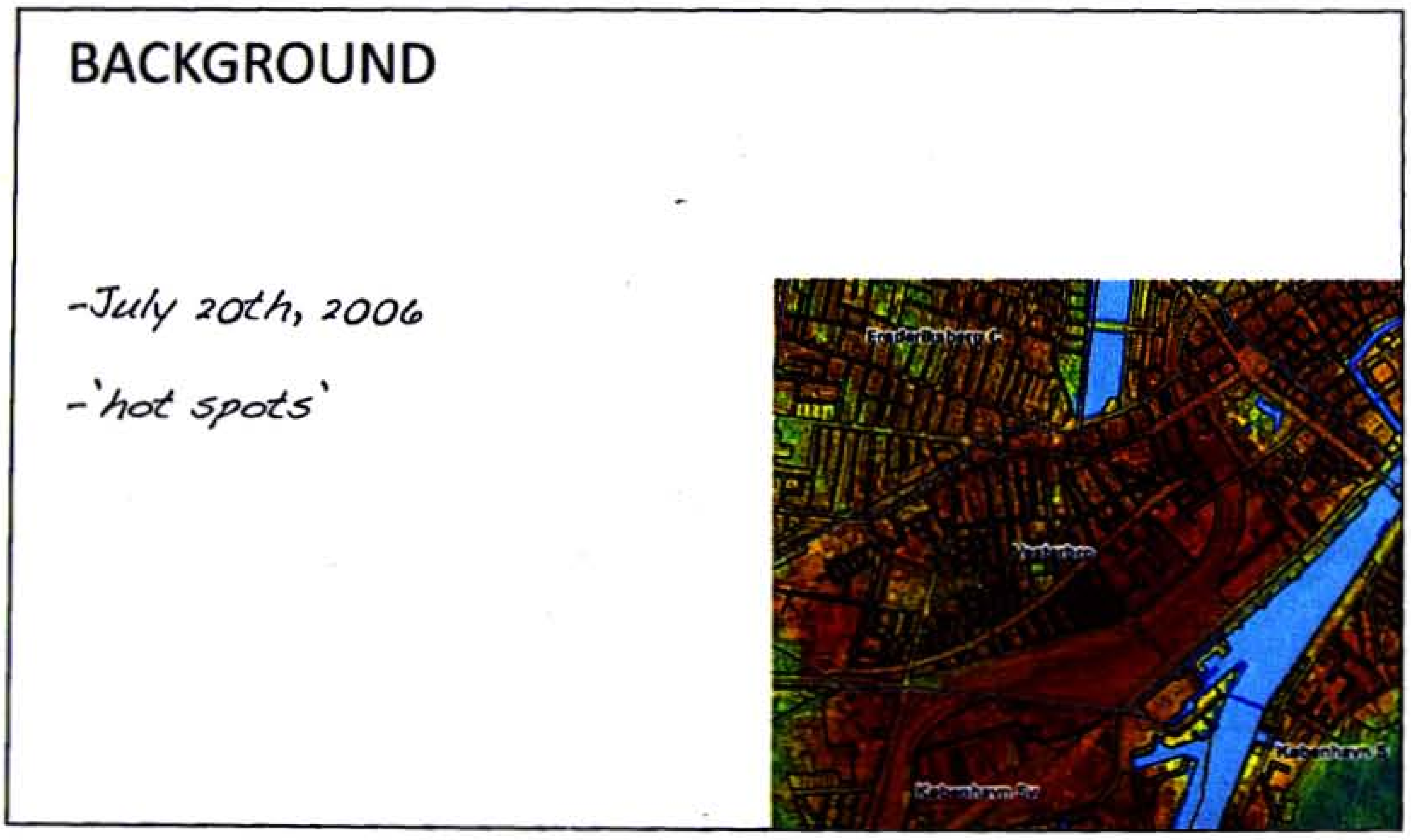
Slide Five: GIS map created for presentation displaying DMI's heat wave danger zones for July 20th, 2006



PRIORITY AREAS

-raster calculator: +2° C

Slide Six: GIS map created for presentation displaying DMI's heat wave danger zones for July 20th, 2006 with two degrees uniformly added with reference to the expected influence of climate change

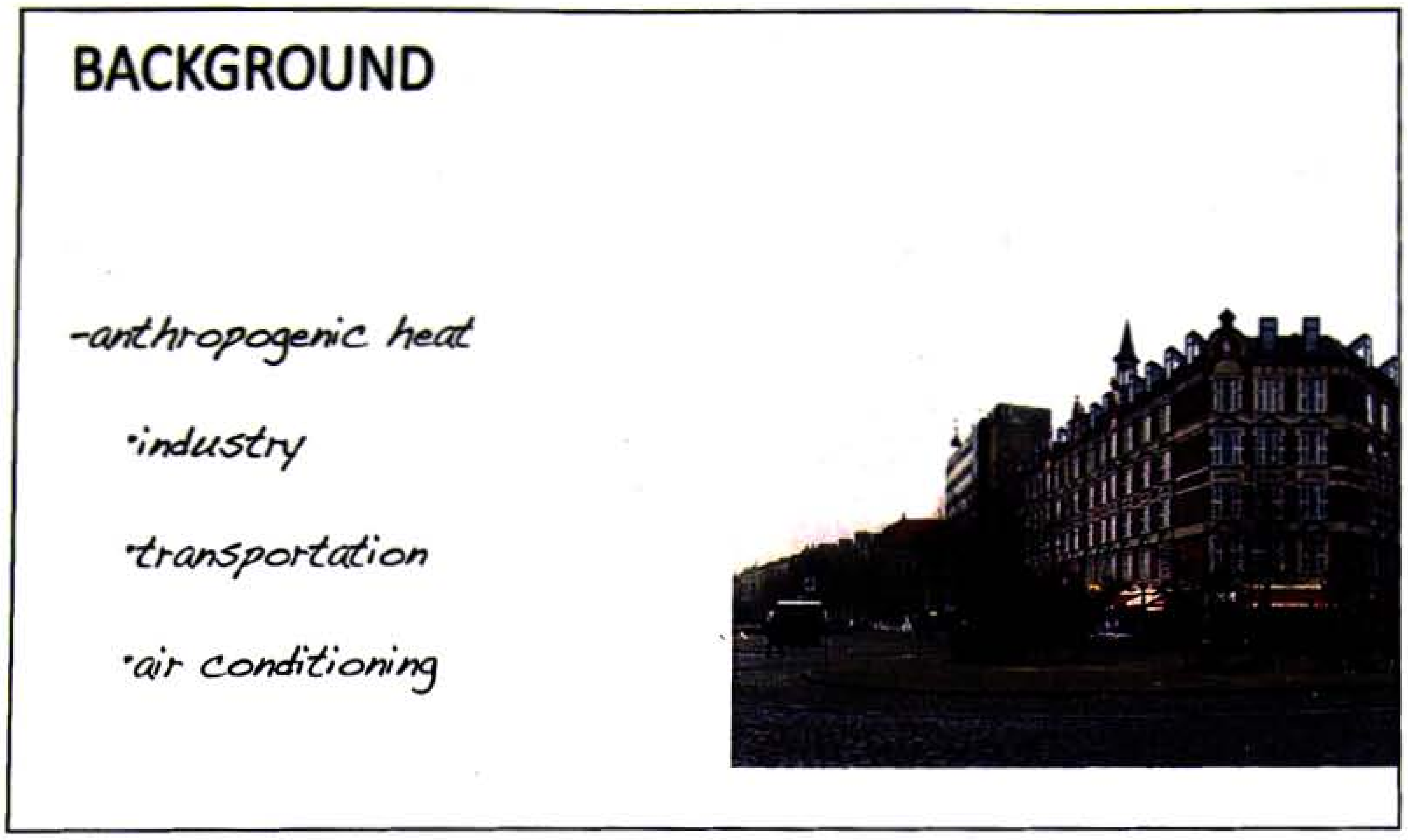


BACKGROUND

-July 20th, 2006

-'hot spots'

Slide Seven: GRAS map showing hottest place in Copenhagen on July 20th, 2006 in the industrial Vesterbro neighborhood

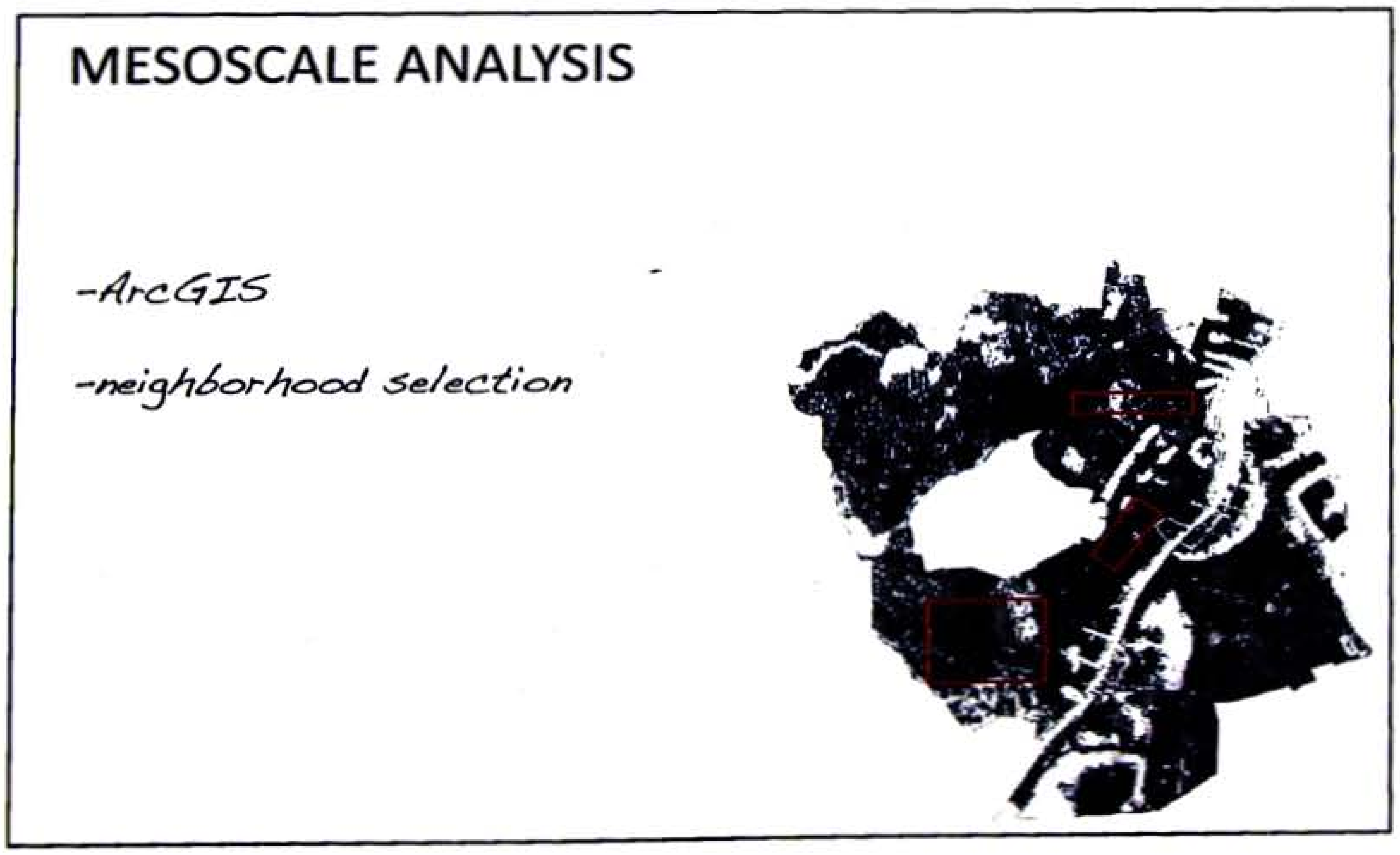


BACKGROUND

-anthropogenic heat

- ·industry
- ·transportation
- ·air conditioning

Slide Eight: Explanation of anthropogenic heat sources' contribution to the urban surface energy balance with a focus on industrial waste heat sources

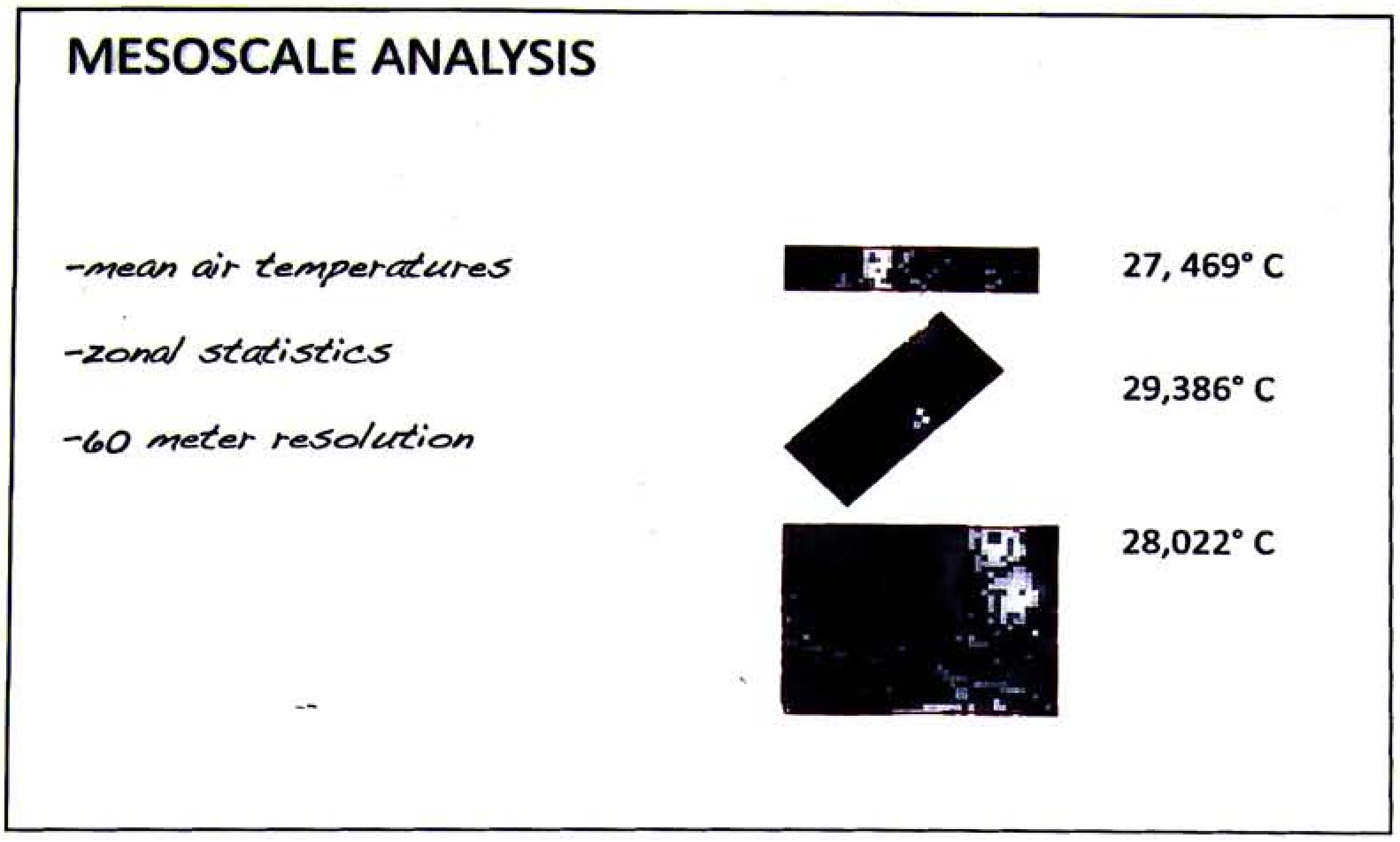


MESOSCALE ANALYSIS

-ArcGIS

-neighborhood selection

Slide Nine: Example of GIS analysis using arbitrary neighborhood aggregation units instead of urban canyons



MESOSCALE ANALYSIS

-mean air temperatures

-zonal statistics

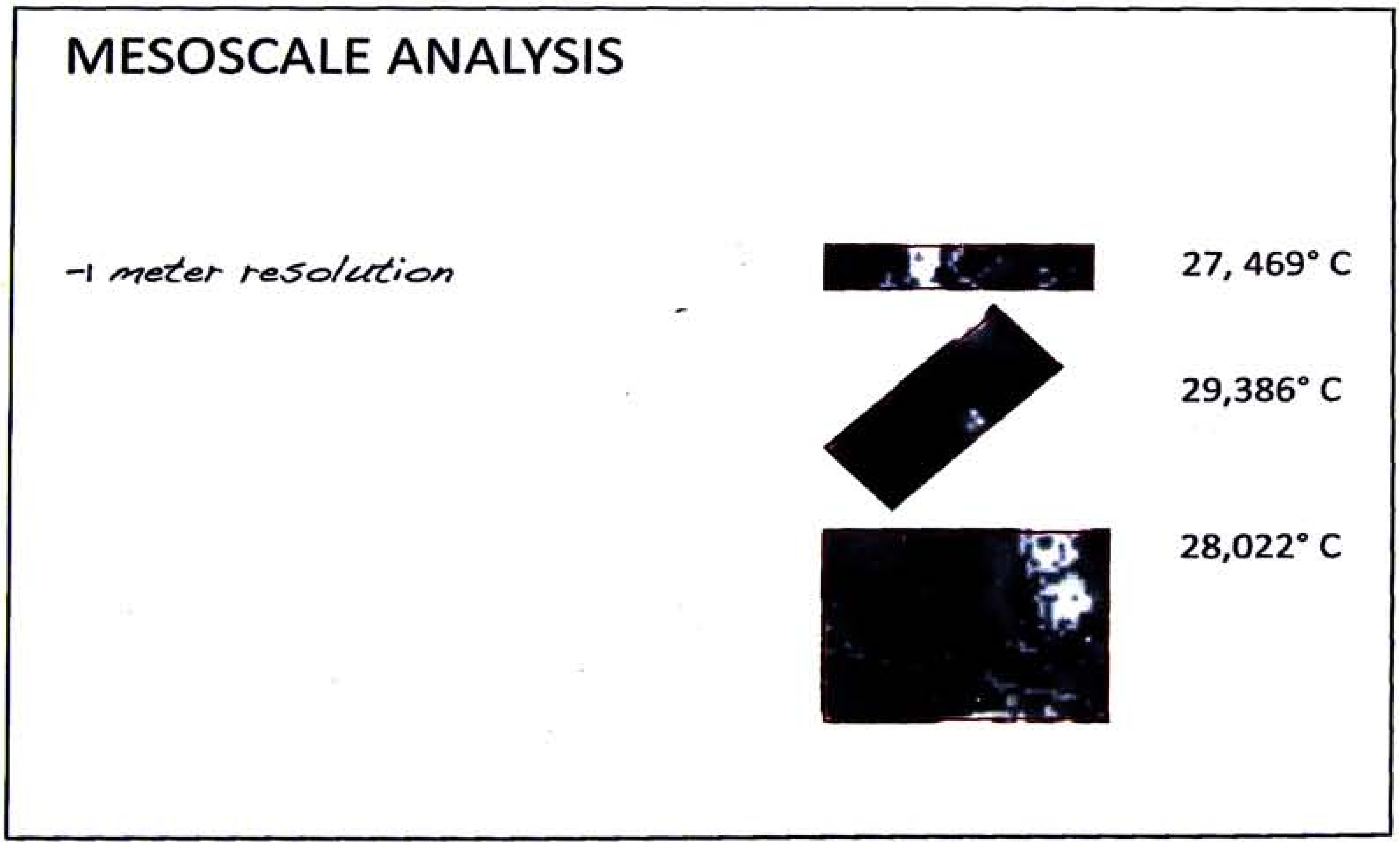
-60 meter resolution

27, 469° C

29,386° C

28,022° C

Slide 10: Explanation of ArcMap zonal statistics air temperature calculation with 60-meter x 60-meter cells



MESOSCALE ANALYSIS

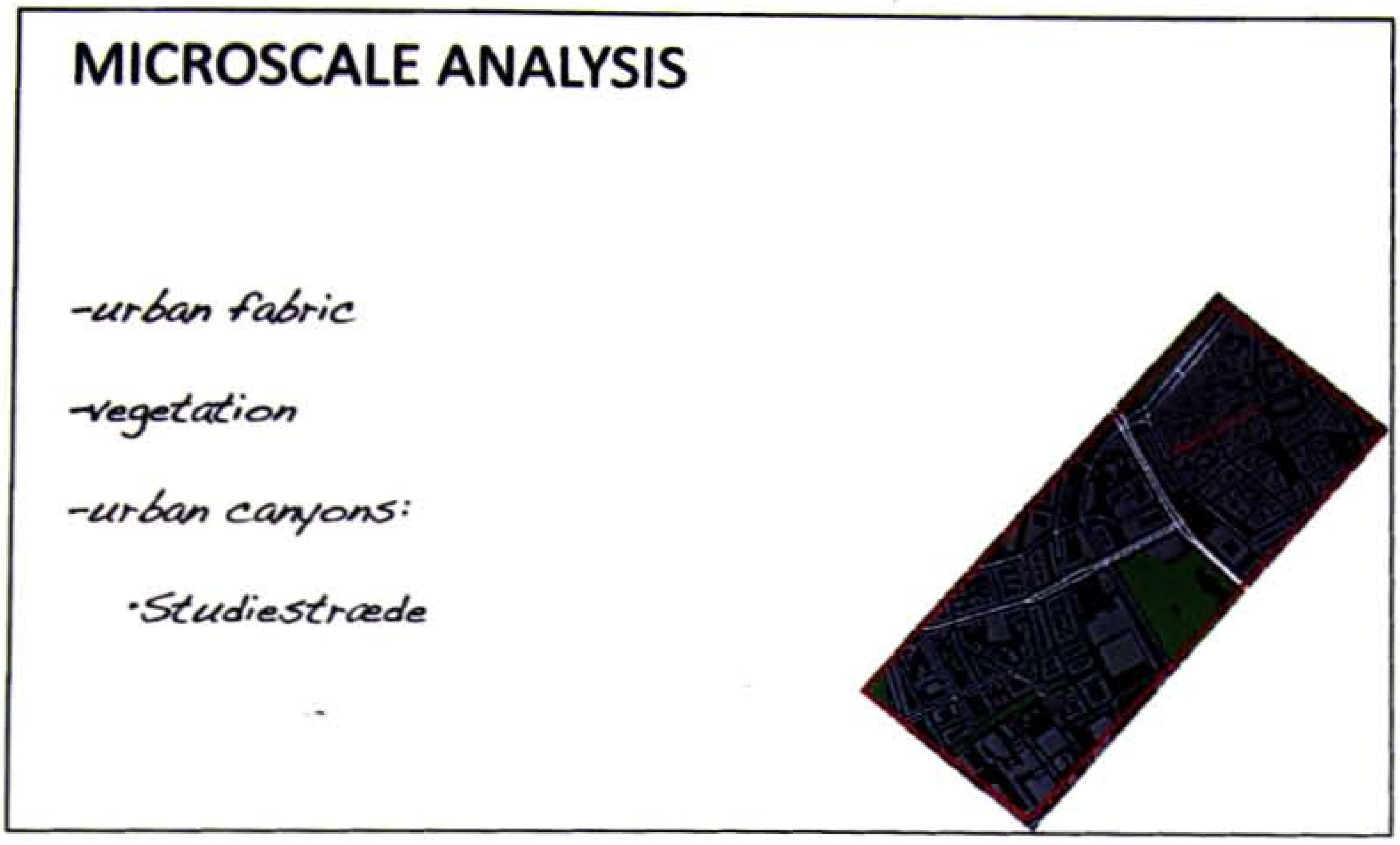
-1 meter resolution

27, 469° C

29,386° C

28,022° C

Slide 11: Explanation of ArcMap zonal statistics air temperature calculation with one-meter x one-meter cells following bilinear resampling from 60-meter x 60-meter cell resolution



MICROSCALE ANALYSIS

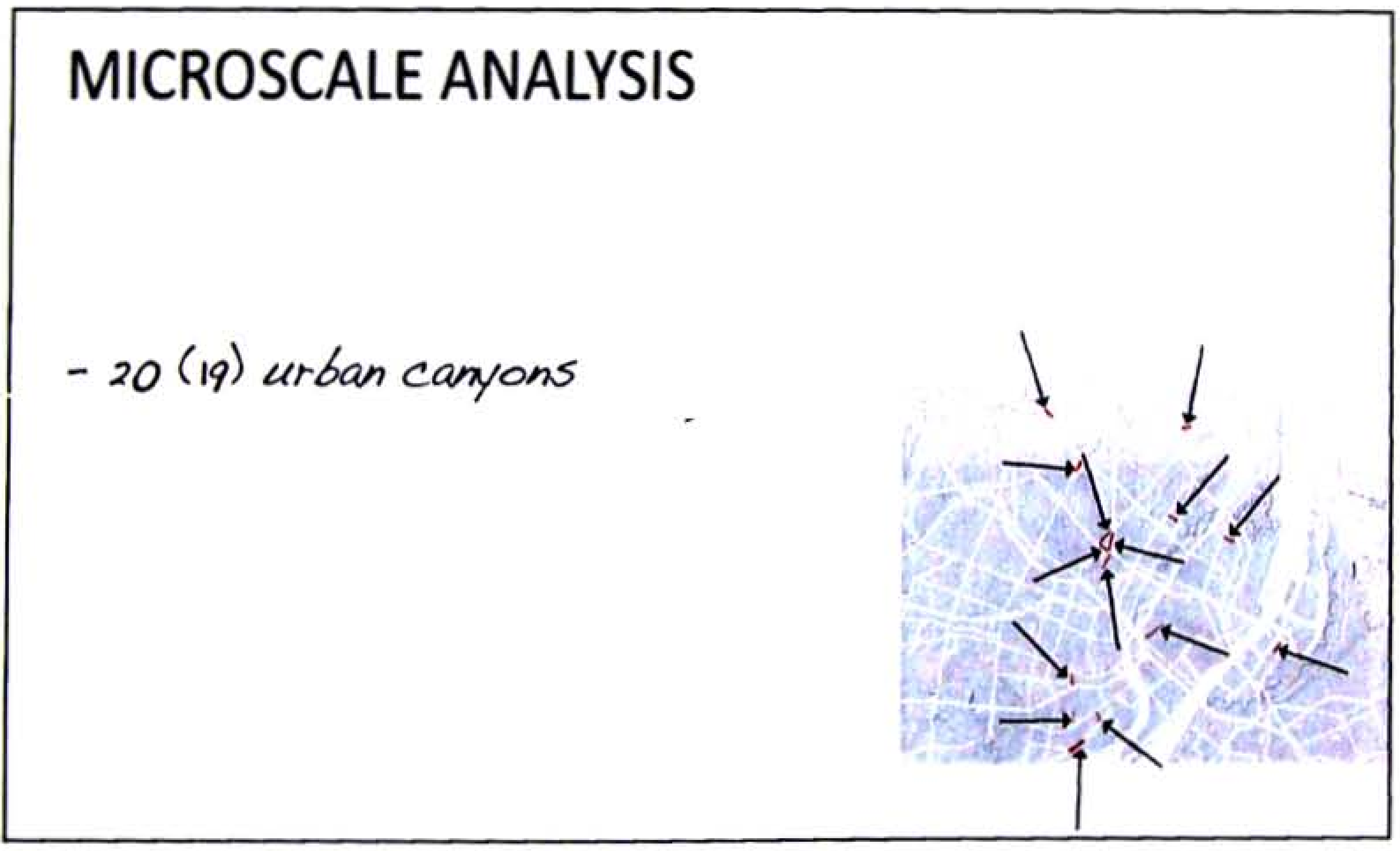
-urban fabric

-vegetation

-urban canyons:

- Studiestræde

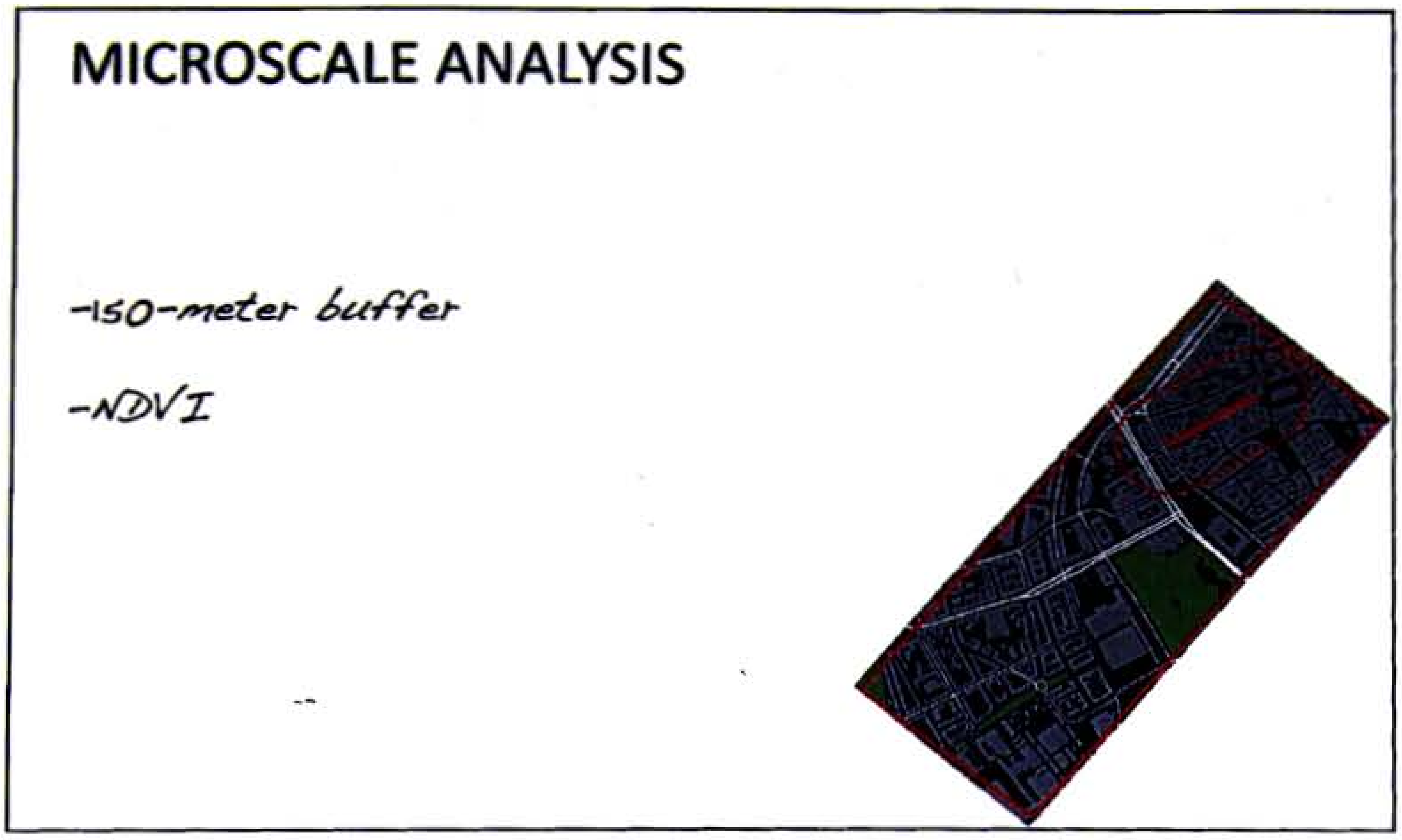
Slide 12: Introduction to microscale analysis



MICROSCALE ANALYSIS

- 20 (19) urban canyons

Slide 13: Introduction to selection of Copenhagen urban canyons

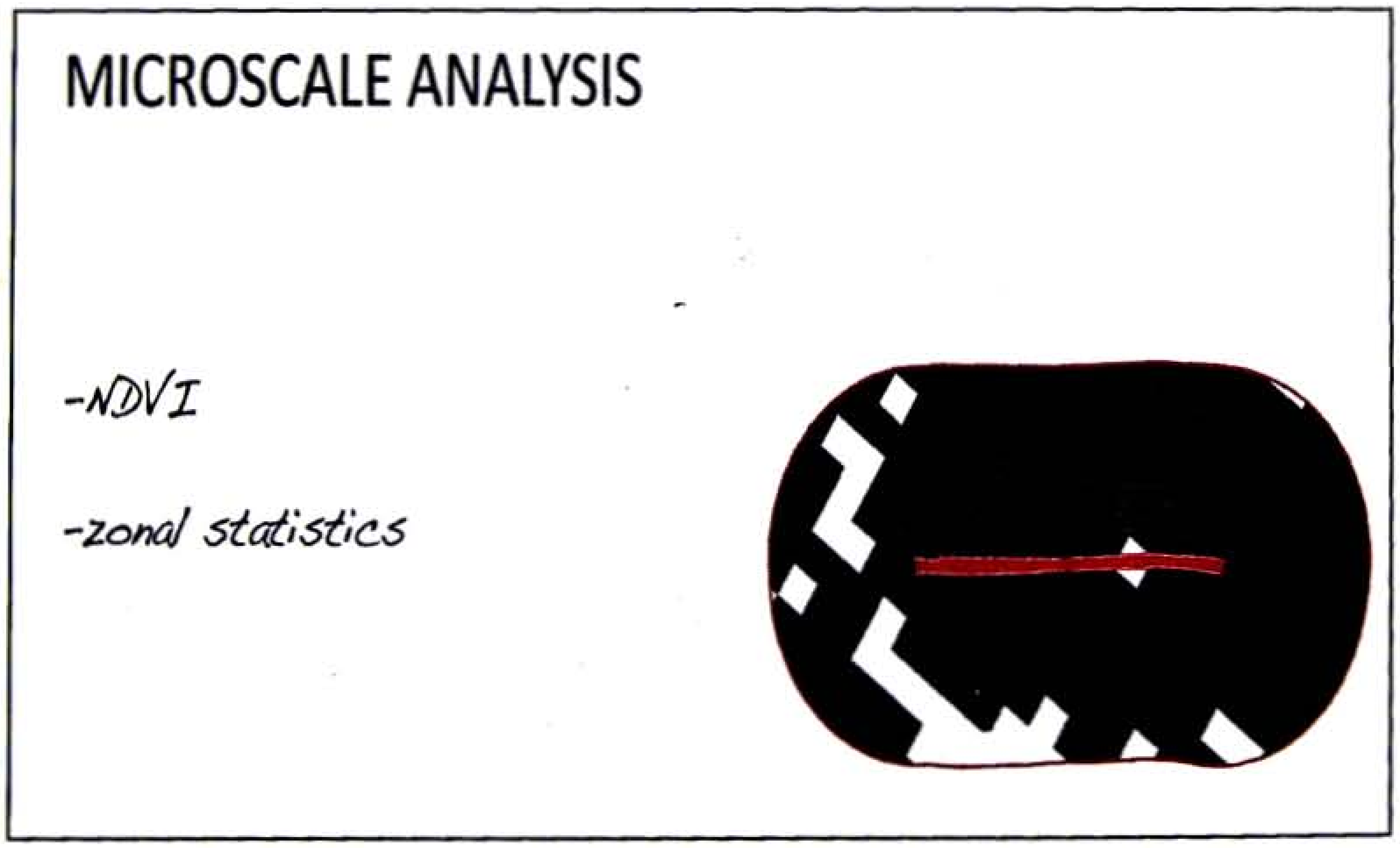


MICROSCALE ANALYSIS

-150-meter buffer

-NDVI

Slide 14: Introduction to 150-meter buffers surrounding urban canyons and the Normalized Difference Vegetation (NDVI) metric



MICROSCALE ANALYSIS

-NDVI

-zonal statistics

Slide 15: Explanation of ArcMap zonal statistics Normalized Difference Vegetation Index (NDVI) calculation with one-meter x one-meter cells following bilinear resampling from 30-meter x 30-meter cell resolution

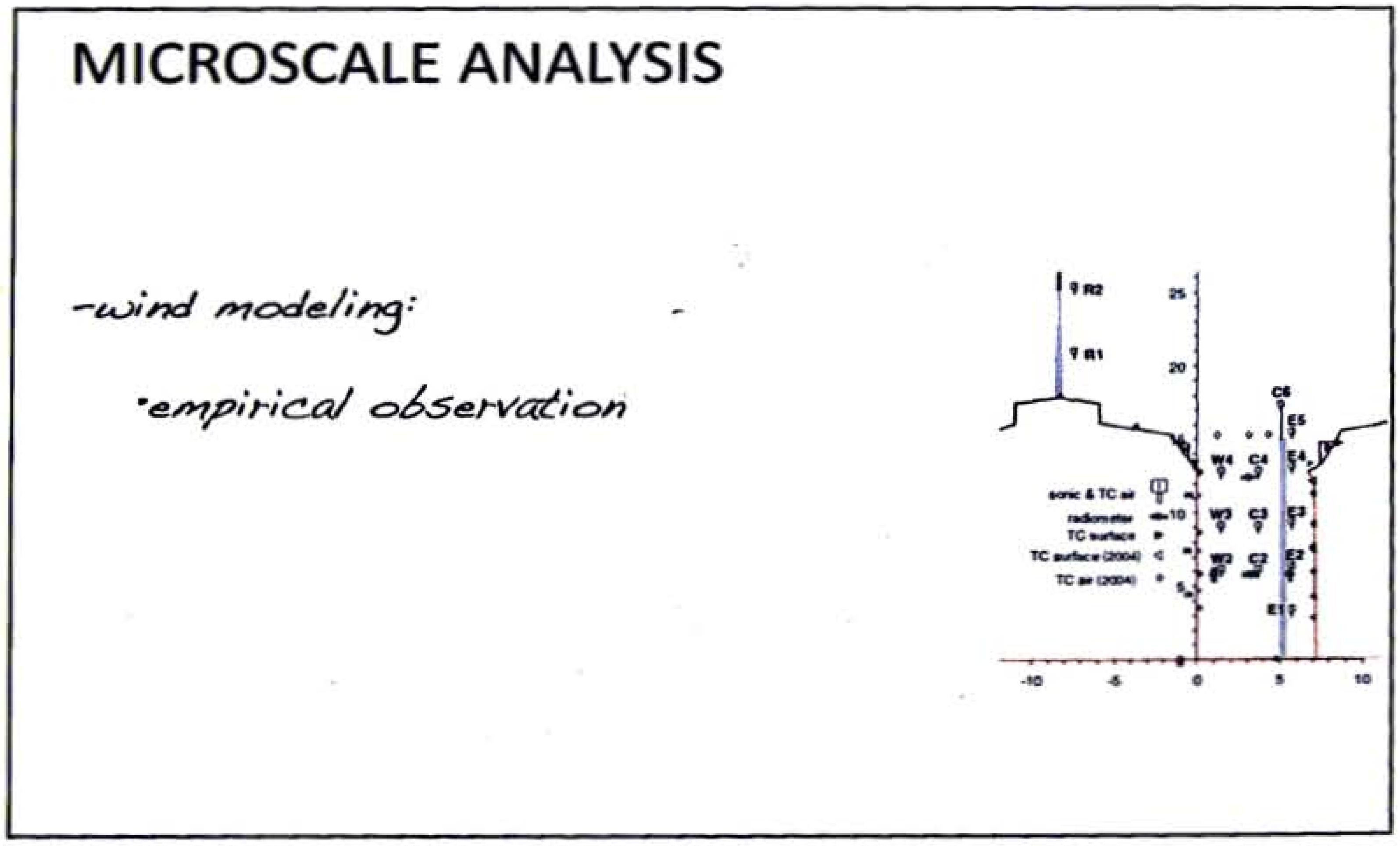
MICROSCALE ANALYSIS

-other intra-urban temperature variation factors:

- *albedo*
- *anthropogenic heat*
- *advection*
- *geometry*

$$Q^* + Q_F = Q_H + Q_E + Q_S + \Delta Q_A$$

Slide 16: Introduction to the urban surface energy balance equation and variables

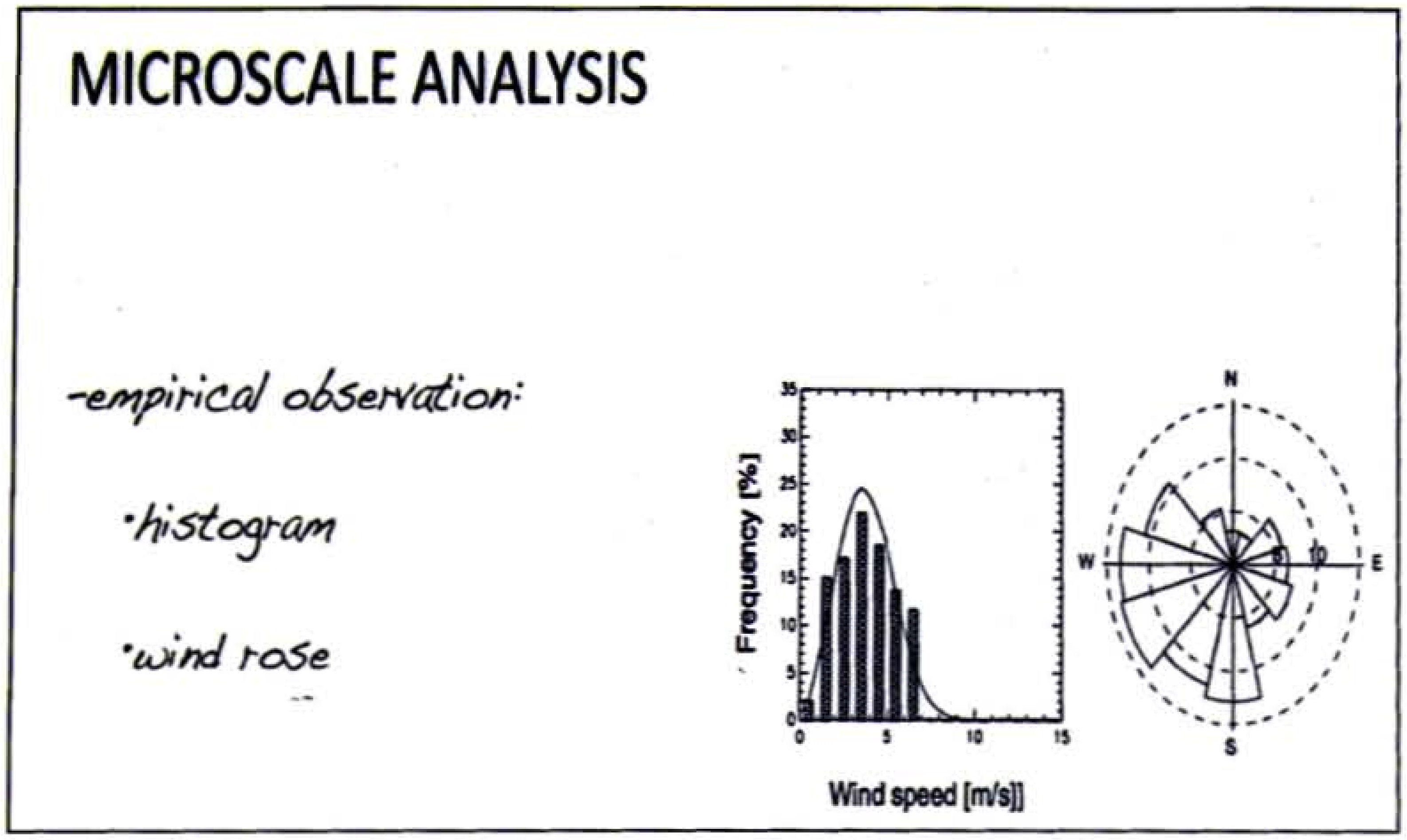


MICROSCALE ANALYSIS

-wind modeling:

- *empirical observation*

Slide 17: Explanation of limitations to modeling wind

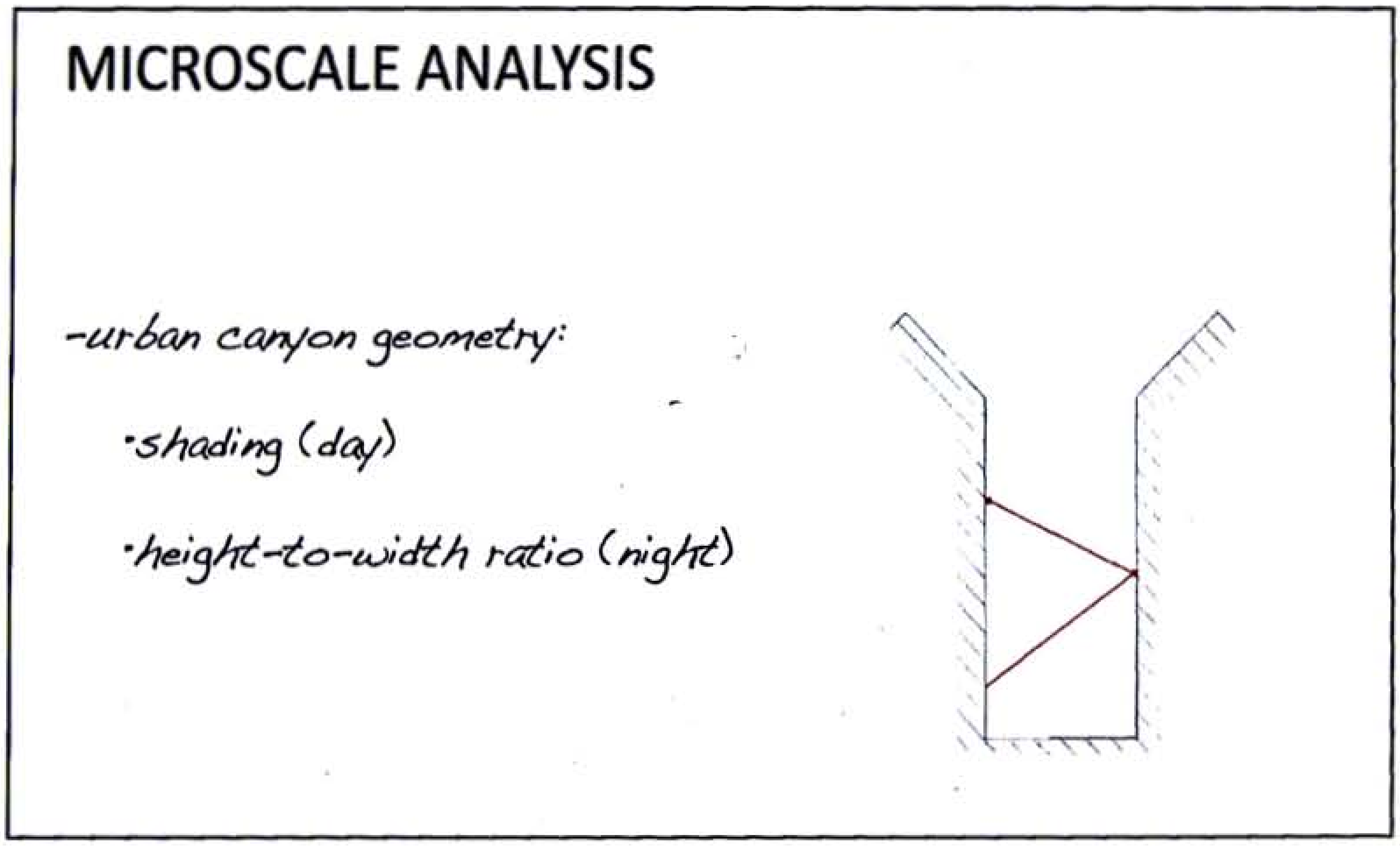


MICROSCALE ANALYSIS

-empirical observation:

- histogram
- wind rose

Slide 18: Continued explanation of limitation to modeling wind

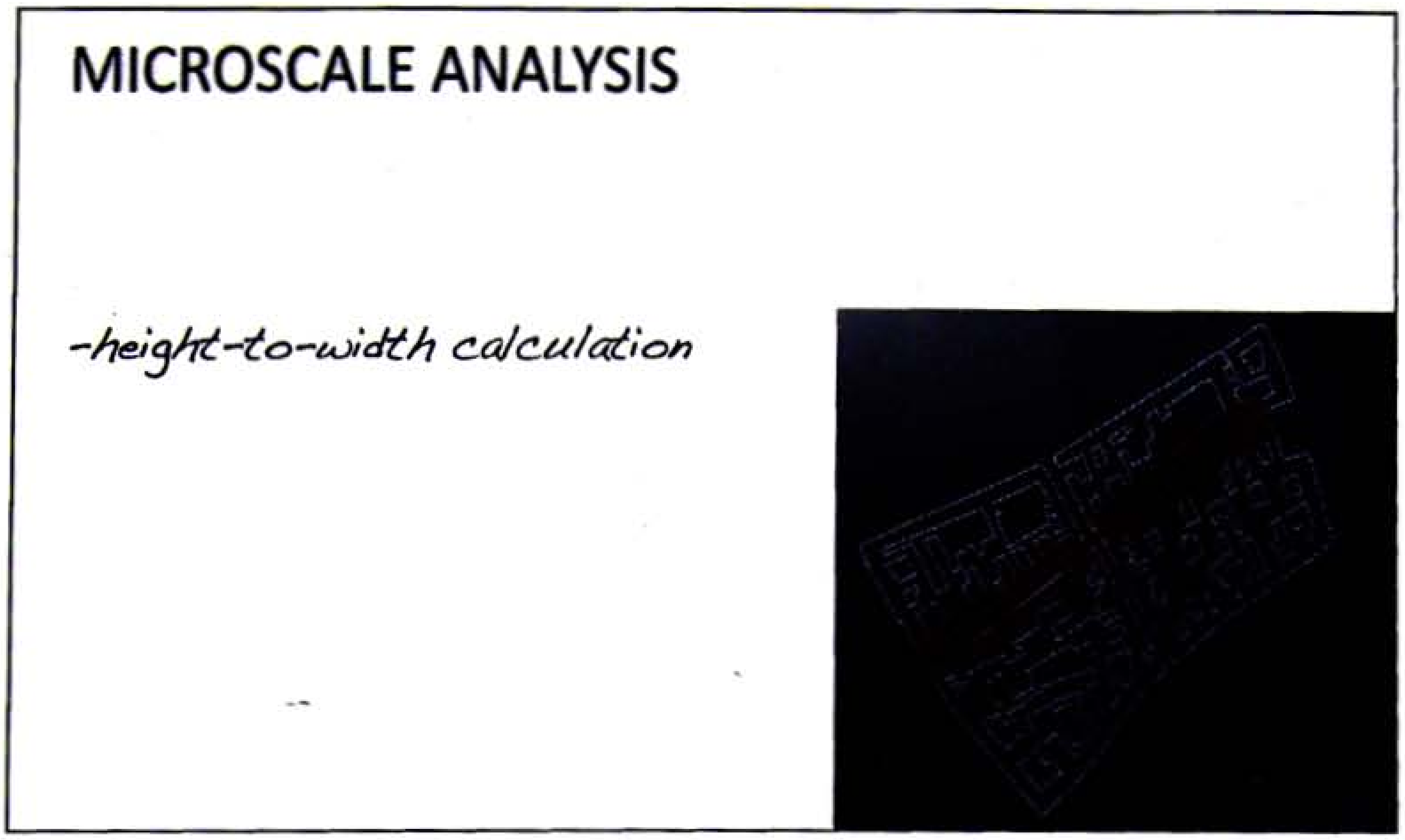


MICROSCALE ANALYSIS

-urban canyon geometry:

- shading (day)
- height-to-width ratio (night)

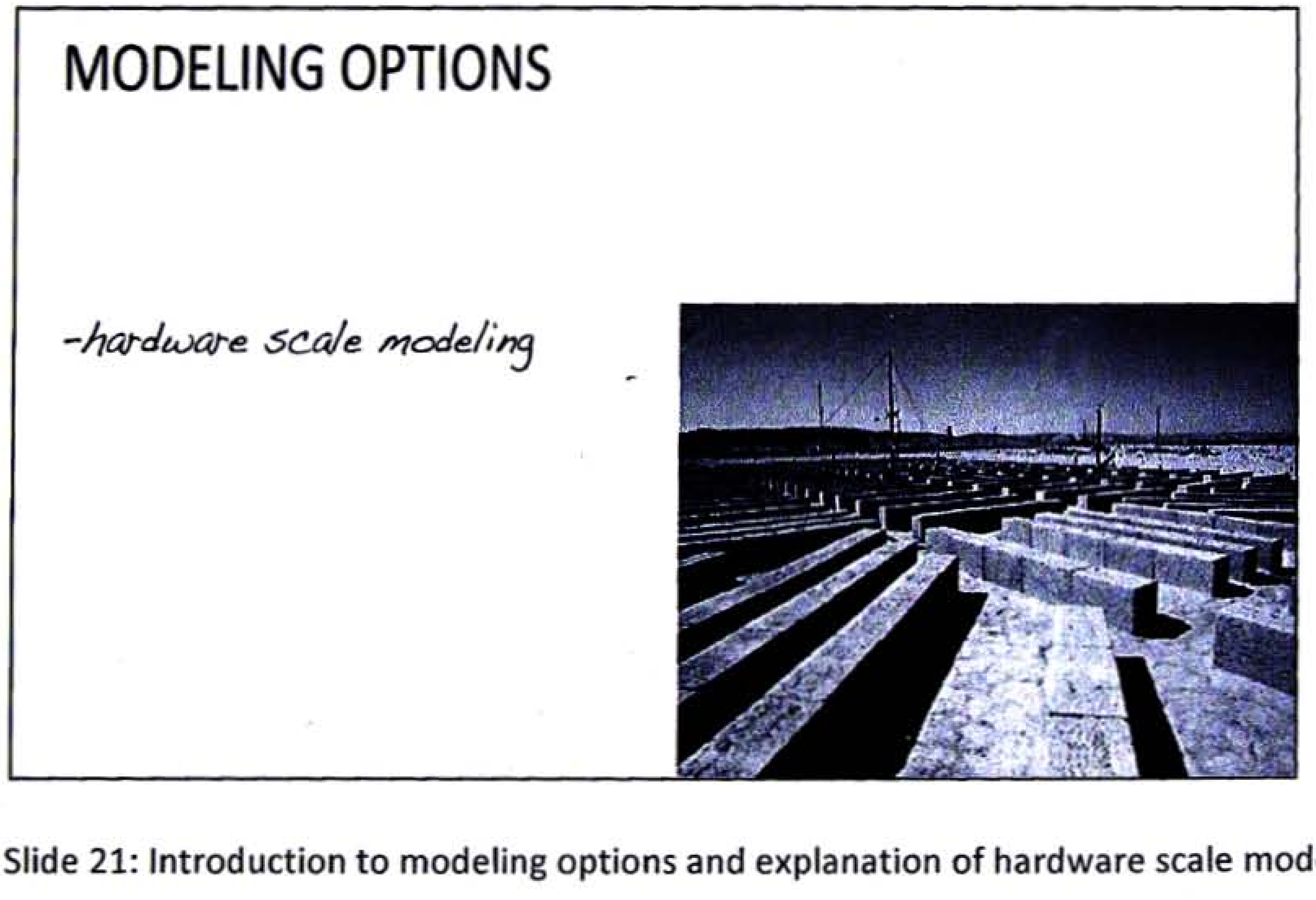
Slide 19: Explanation of urban canyon openness and height-to-width ratio metric



MICROSCALE ANALYSIS

-height-to-width calculation

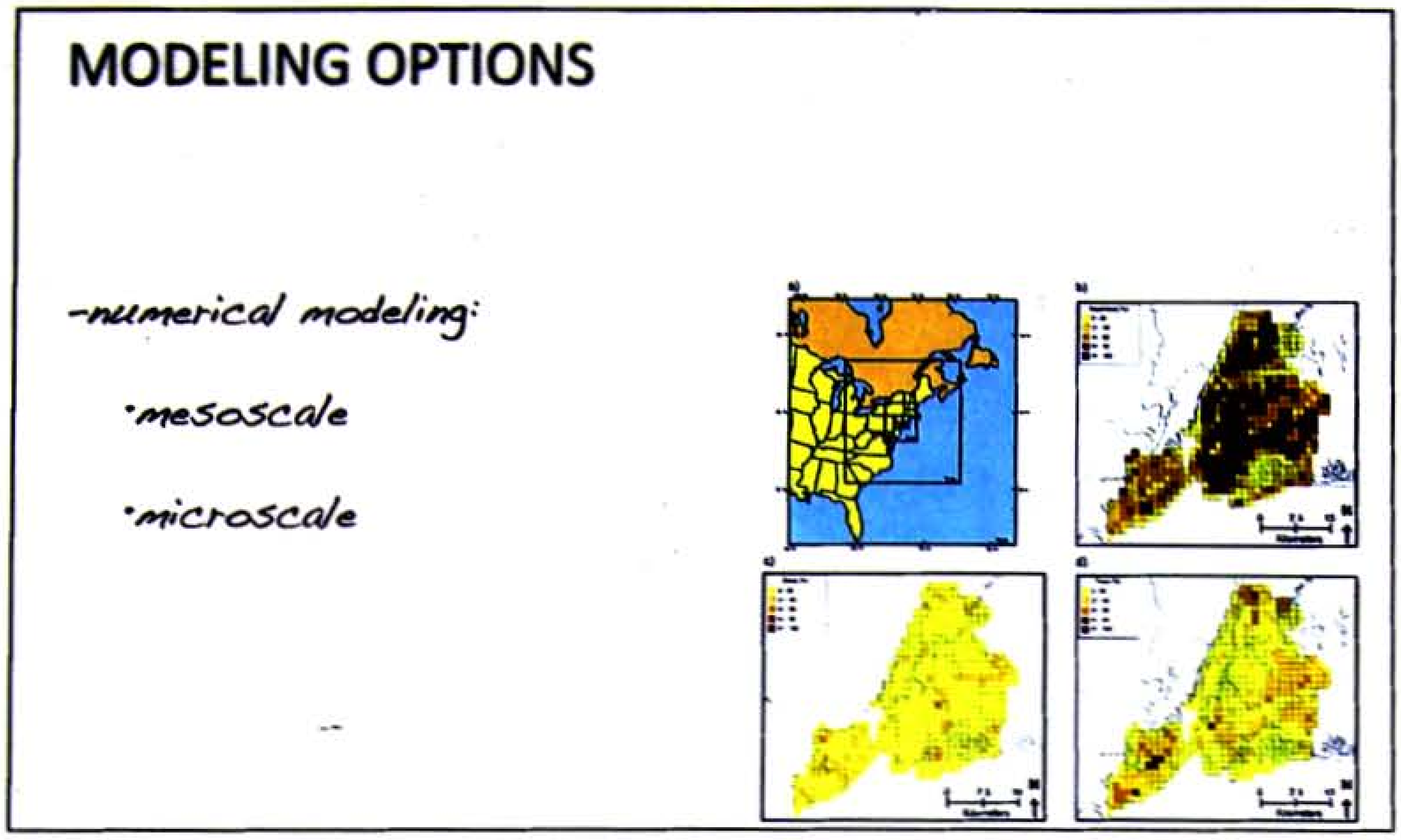
Slide 20: Explanation of urban canyon height-to-width ratio GIS calculation



MODELING OPTIONS

-hardware scale modeling

Slide 21: Introduction to modeling options and explanation of hardware scale modeling

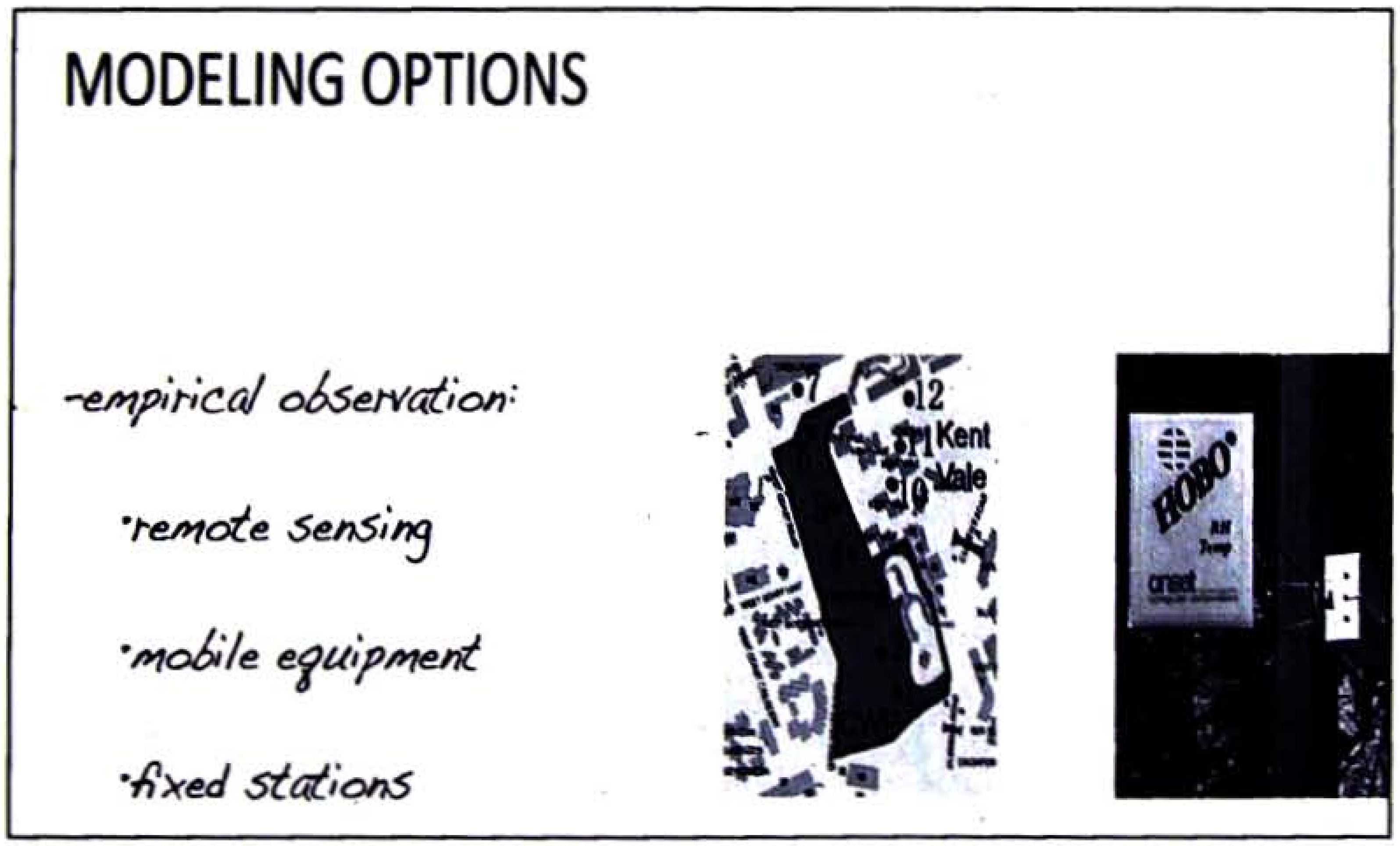


MODELING OPTIONS

-numerical modeling:

- mesoscale
- microscale

Slide 22: Explanation of numeric computer modeling at two scales

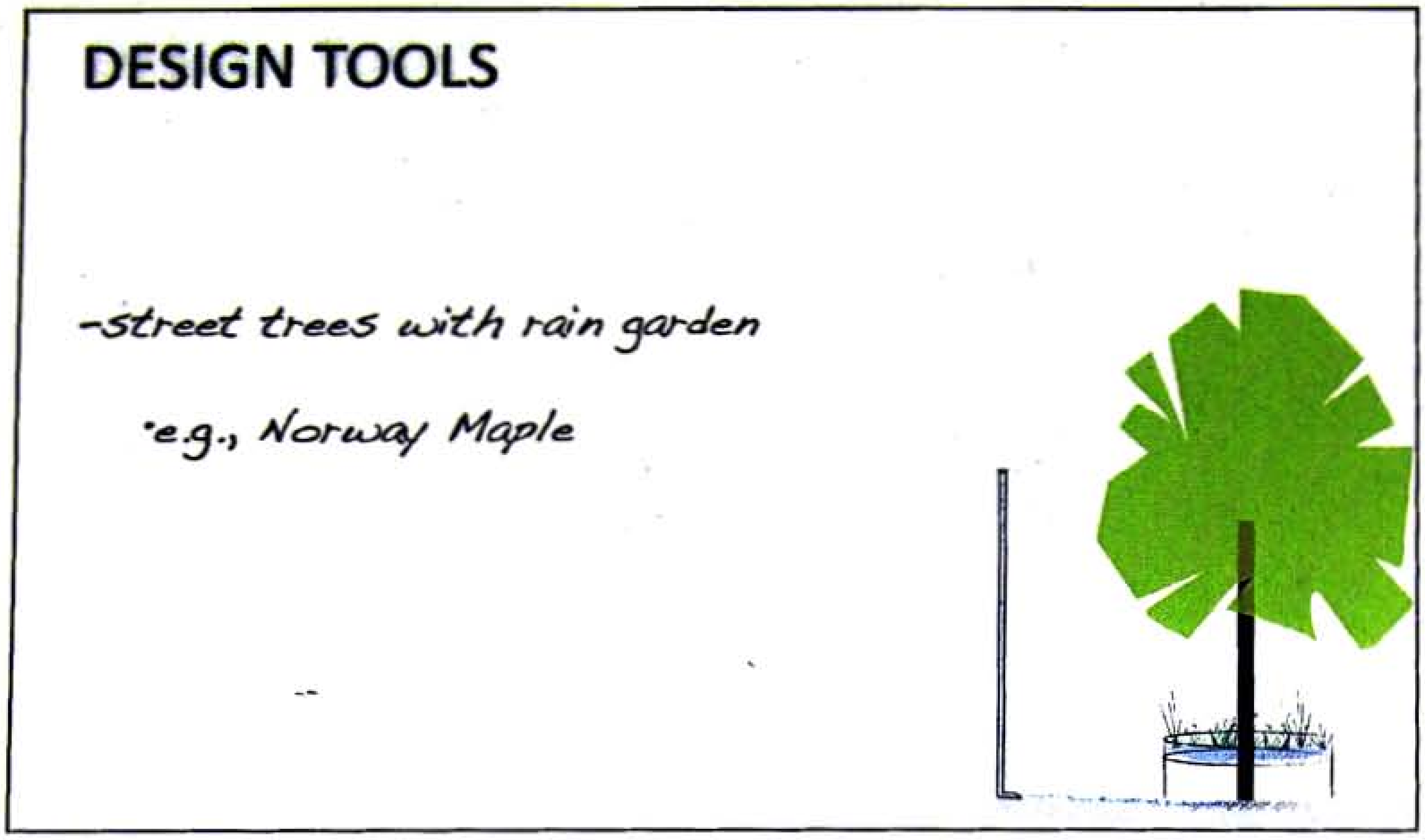


MODELING OPTIONS

-empirical observation:

- remote sensing
- mobile equipment
- fixed stations

Slide 23: Explanation of empirical observation modeling options and methods

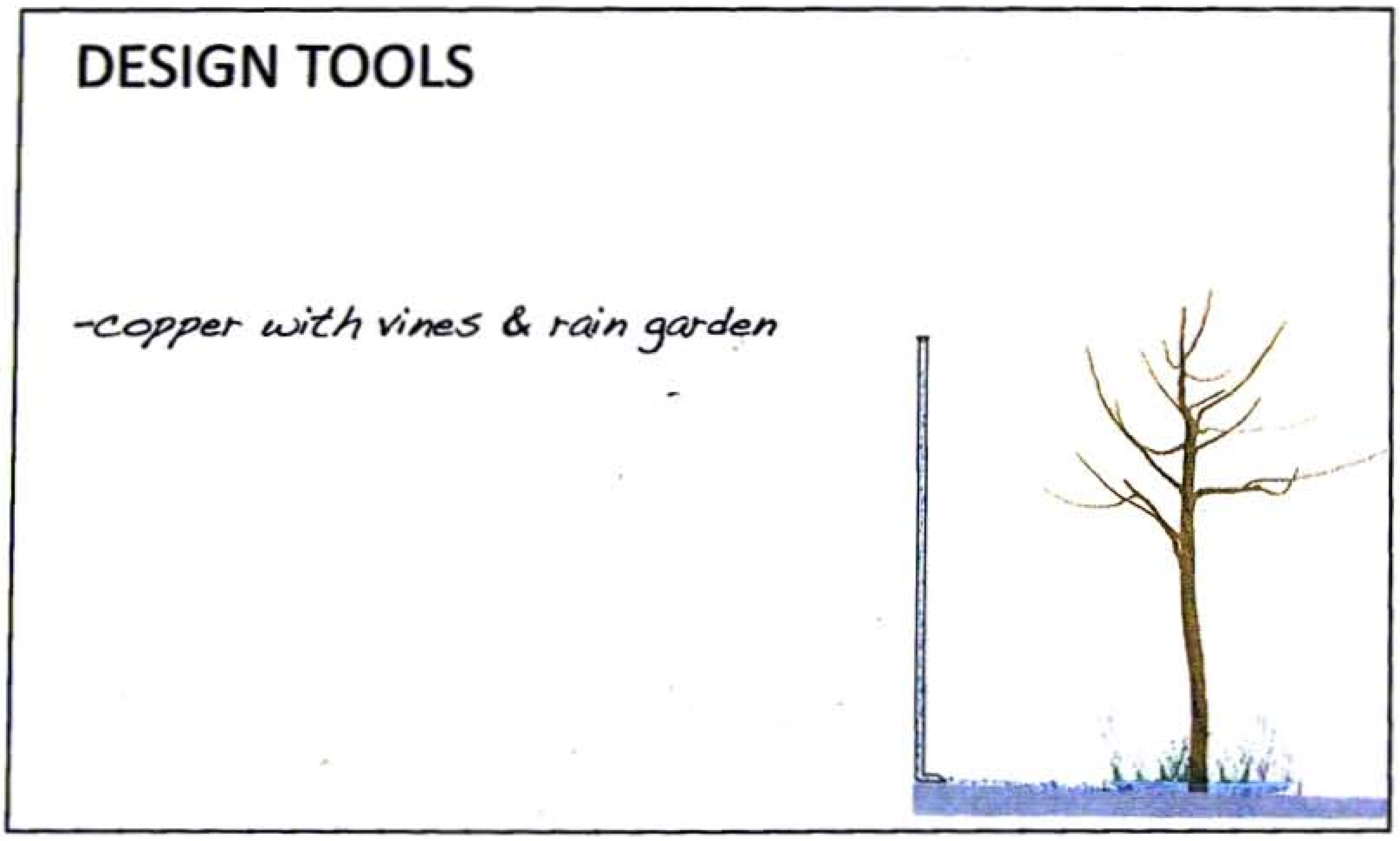


DESIGN TOOLS

-street trees with rain garden

- e.g., Norway Maple

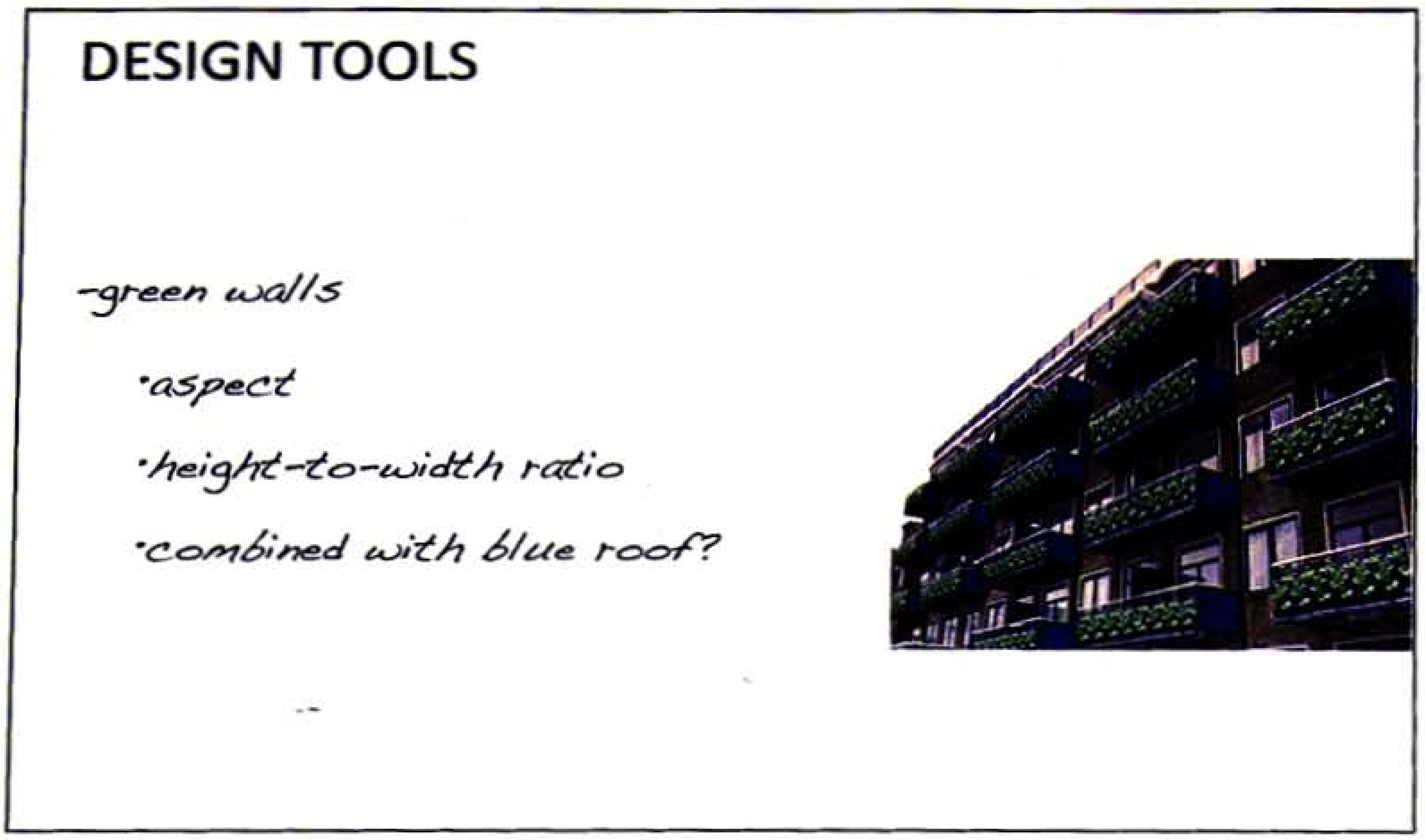
Slide 24: Explanation of preliminary green infrastructure designs created for this presentation



DESIGN TOOLS

-copper with vines & rain garden

Slide 25: Continuation of explanation of preliminary green infrastructure designs created for this presentation

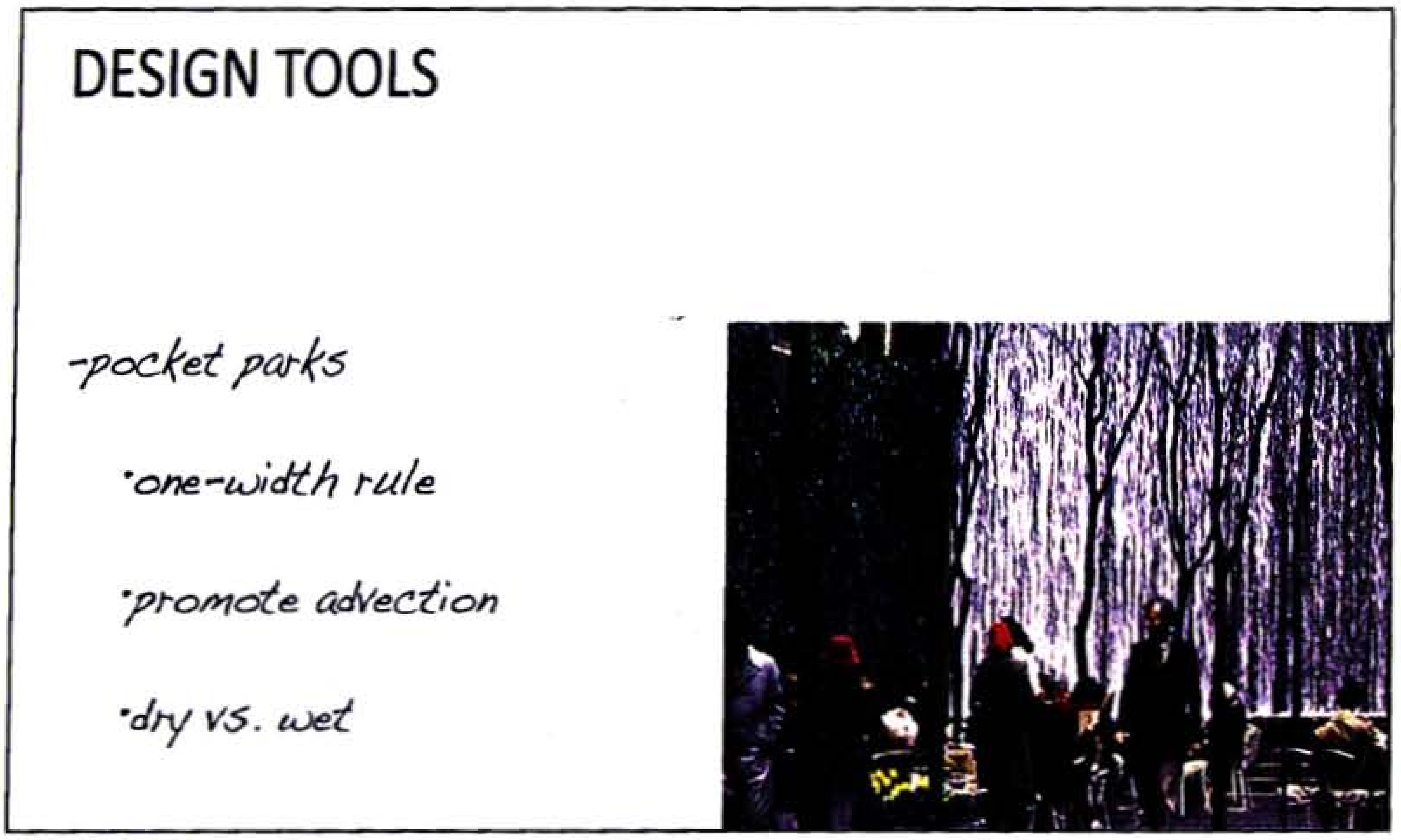


DESIGN TOOLS

-green walls

- aspect
- height-to-width ratio
- combined with blue roof?

Slide 26: Discussion of other green infrastructure elements with potential cooling attributes

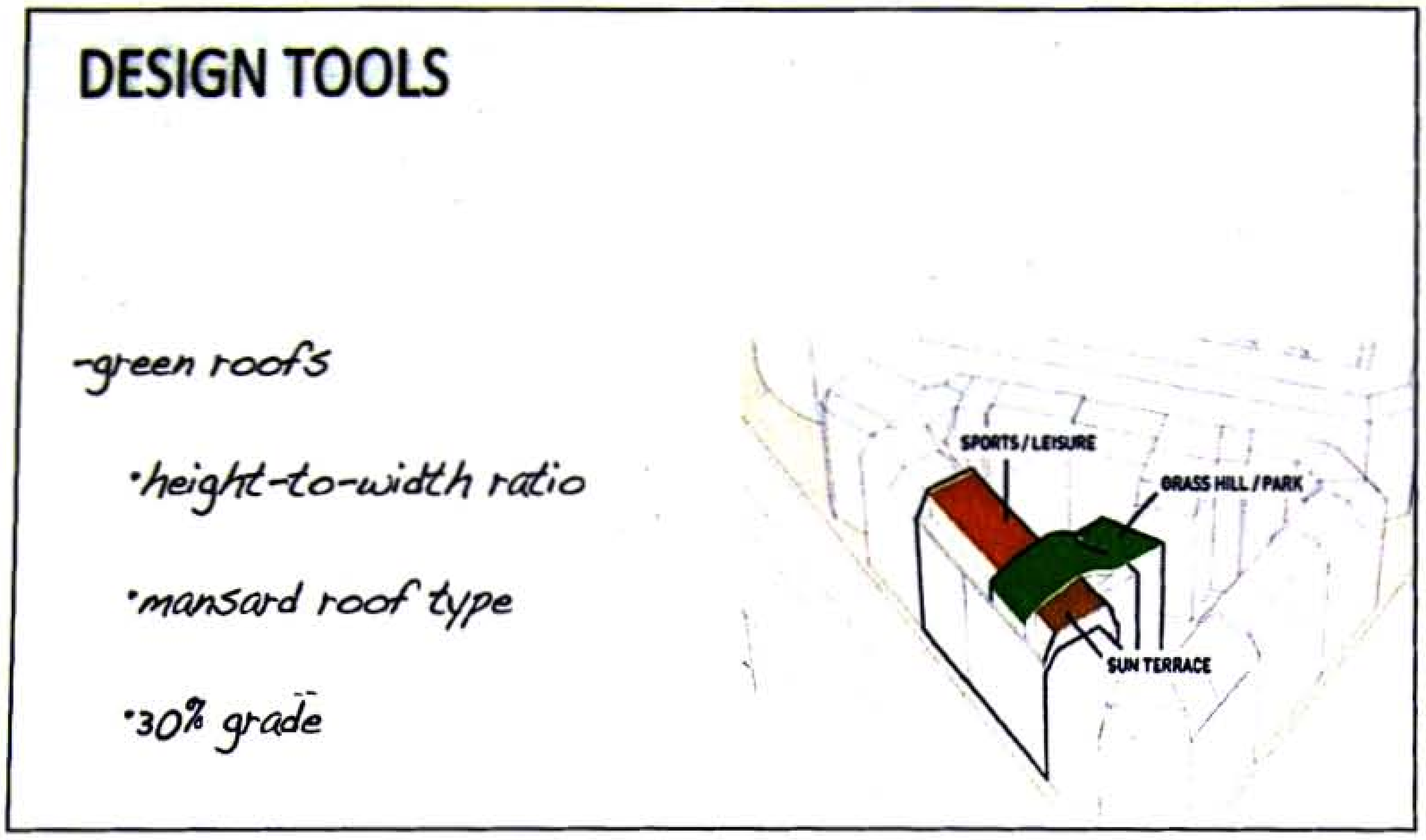


DESIGN TOOLS

-pocket parks

- one-width rule
- promote advection
- dry vs. wet

Slide 27: Continuation discussion of other green infrastructure elements with potential cooling attributes



DESIGN TOOLS

-green roofs

- height-to-width ratio
- mansard roof type
- 30% grade

Slide 28: Continuation discussion of other green infrastructure elements with potential cooling attributes

CONCLUSION

I was asked by faculty members at the University of Copenhagen in 2011 to research the urban heat island in Copenhagen, which is a concern due to the danger posed by urban heat waves in the summer months to a population unaccustomed to extreme temperatures. My research was intended to support the later creation of a climate adaptation plan for the city. To be able to make recommendations for further inquiry, it became clear that I would need to understand the urban surface energy balance. To this end, I consulted research articles in climatology journals. With an understanding of the urban surface energy balance variables, I was able to pursue a GIS-based spatial statistics analysis, modeling as many of the urban surface energy balance variables as possible. However, I was only able to access data to represent two of the variables. Fortunately, the urban canyon openness variable, represented by the Normalized Difference Vegetation Index, was of great interest to the University of Copenhagen. The 2010 University of Copenhagen report had also conducted a spatial statistics analysis correlating surface temperature to Normalized Difference Vegetation Index levels. My analysis, generally speaking, corroborated the results from the 2010 report and introduced two spatial aggregation units to the discussion, the urban canyon and its 150-meter buffer.

The next step was to research how Copenhagen urban canyons might be cooled by green infrastructure, which, by definition, is composed of vegetation. Adding green infrastructure elements, such as street trees, urban parks, and green roofs, to the 150-meter buffer zones surrounding the urban canyon should therefore increase the Normalized Difference Vegetation Levels of these areas. My GIS-based spatial statistics analysis had shown a statistically significant relationship between the Normalized Difference Vegetation Index level of the 150-meter buffer area surrounding an urban canyon and the canyon's air temperature. With this premise, I began researching the mechanisms by which cool air is produced by vegetation and transported horizontally across the urban fabric. More specifically, I looked at the potential for green infrastructure elements to generate cool air for horizontal transport.

I found that current research suggests that urban parks are the most favorable option to cool urban canyons. I was asked by representatives from the University of Copenhagen how many degrees of cooling within an urban canyon might be expected from the addition of an urban park to the area surrounding the canyon. I was unable to answer this question based on my review of pertinent literature. As such, I recommended that the University of Copenhagen pursue more extensive modeling research using some combination of numeric, hardware scale, and empirical observation methods. I would recommend the same to representatives from any city who are considering employing green infrastructure elements for the purpose of urban heat island reduction.

Such research might begin with a numeric computer modeling simulation for a set of adjacent Copenhagen urban canyons using the Local-Scale Urban Meteorological Parameterization Scheme or the National Center for Atmospheric Research Mesoscale Model. Each of these models is able to incorporate more independent climatic and urban form variables than was possible with my GIS-based spatial statistics study. These models are both capable of returning temperature change outputs, which could be observed with changes to urban form characteristics, such as wind or the Normalized Difference Vegetation Index. Of course, some assumptions would be required for input into the model, so empirical observations could be used to support assumptions. For example, assumptions regarding wind direction, frequency, and velocity could be supported by direct empirical measurement within a representative sample of urban canyons. If researchers were able to return reliable results with regard to the temperature change to a set of canyons as a result of input changes to Normalized Vegetation

Index levels, the next step would be to consider what type(s) of green infrastructure to introduce to individual urban canyons and/or their surroundings. Hardware scale models mimicking the urban form characteristics of individual urban canyons and their immediate surroundings could be constructed to model the additions of green roofs, street trees, and urban parks for the purpose of predicting temperature changes within the urban canyons.

Without access to a computer numeric model, I attempted to model Copenhagen urban canyon intra-urban temperature variation with a GIS platform. My results indicated that the Normalized Difference Vegetation Index levels of the areas (150-meter buffers) surrounding Copenhagen urban canyons significantly affected their average air temperature. Given this result, I then consulted academic journal articles with the idea that I might be able to predict how many degrees of cooling additions of green infrastructure in the buffer areas might contribute. The studies I consulted in academic journals, however, were based on case studies and idealized urban geometries. Without studies specific to Copenhagen, it was not possible to predict how many degrees of cooling various types of green infrastructure might provide. As such, I attempted to create design principles for introducing green infrastructure elements within and around Copenhagen urban canyons based on general principles extracted from the literature. To this aim, I attempted to create an algorithm by which one could select a green infrastructure element for an urban canyon based on the climatic and urban form particularities of the urban canyon. One of my initial algorithmic diagram sketches is shown in Figure 12.

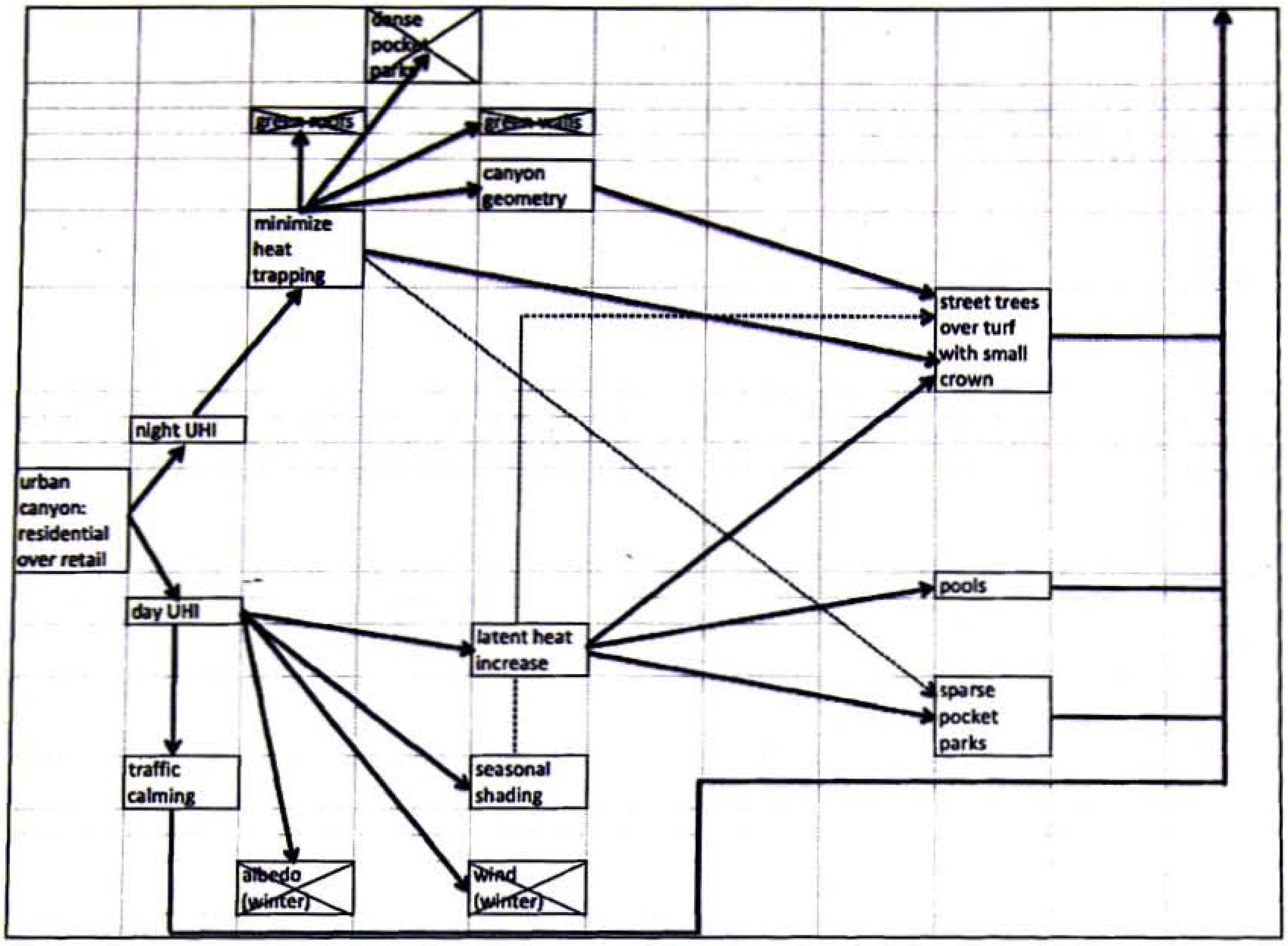


Figure 12: Example of algorithmic design intervention sketch

I soon found, however, that rigidly applying such principles was a questionable endeavor given the many interacting attributes of a real world urban canyon. In my opinion, an existing urban canyon should be assessed on an individual basis before a green infrastructure element intervention is prescribed. A practitioner should consider the level and type of human activity in the canyon in conjunction with all of the climatic and urban form characteristics herein described. However, I also believe that my findings warrant additional modeling studies to more comprehensively evaluate the air temperature effects that urban form and climatic attributes have on a representative sample of Copenhagen urban canyons. More information on Copenhagen urban canyons' intra-urban temperature variation would provide a more substantial basis on which to evaluate urban canyons individually for design intervention. Effectively, if I were to redo this study, I would likely have more aggressively sought access to one of the microscale or neighborhood scale numeric computer models and accompanying empirical observation data to support input assumptions to one or more numeric computer models. Generally speaking, this conclusion aligns with the urban design practice of observing site-specific attributes prior to design intervention.

WORKS CITED

Arnfield, John. "Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island," *International journal of Climatology* 23 (2003): 1-26.

Barring, L., J.O. Mattson, and S. Lindquist. "Canyon geometry, street temperatures and urban heat island in Malmö, Sweden," *International Journal of Climatology* 5 (1985): 333-444.

Bass, Brad. "Mitigating the urban heat island with green roof infrastructure." Paper presented at the Urban Heat Island Summit, Toronto, May 1-4, 2002.

Chapman, L., J.E. Thornes, and A. V. Bradley. "Rapid determination of canyon geometry parameters for use in surface radiation budget," *Theoretical and Applied Climatology* 69 (2001): 81-89.

Chen, L., E. Ng, X. An, C. Ren, M. Lee, U. Wang, and Z. He. "Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: A GIS-based simulation approach," *International Journal of Climatology* 32 (2012): 121-136, (accessed December 2011), doi: 10.1002/joc.2243.

Dimoudi, Argiro and Marialena Nikolopoulou. "Vegetation in the urban environment: microclimatic analysis and benefits," *Energy and Buildings* 35 (2003): 69-76.

Eliasson, I., B. Offerle, C.S.B. Grimmond, and S. Lindqvist. "Wind fields and turbulence statistics in an urban street canyon," *Atmospheric Environment* 40 (2006): 1-16.

Gedzelman, S.D., S. Austin, R. Cermak, N. Stefano, S. Partridge, S. Quesenberry, and D.A. Robinson. "Mesoscale aspects of the urban heat island around New York City," *Theoretical and Applied Climatology* 75 (2003): 29-42.

Gober, P., A. Brazel, S. Myint, R. Quay, S. Grossman-Clarke, A. Miller, and S. Rossi. "Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool Phoenix?," *Journal of the American Planning Association* 76 (2010): 109- 121.

Grimmond, C.S.B., "Climate of Cities," *The Routledge handbook of urban ecology*, edited by Ian Douglas, 103-116. Abingdon, Oxon: Routledge, 2011.

Grimmond, C. S. B., and T. R. Oke. "Turbulent Heat Fluxes in Urban Areas: Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS)," *Journal of Applied Meteorology* 41 (2002): 792-810.

Hove, L.W.A., G.J. Steeneveld, C.M.J. Jacobs, B.G. Heusinkveld, J.A. Elbers, E.J. Moors, and A.A.M. Holtslag. "Exploring the urban heat island intensity of Dutch cities," Wageningen: Alterra, 2011. http://edepot.wur.nl/171621 (accessed January 2012).

Jensen, John. *Remote Sensing of the Environment: an Earth Resource Perspective*. Upper Saddle River, N.J.: Pearson Prentice Hall, 2007.

Lindberg, Frederik. "Modeling the urban climate using a local governmental geo- database," *Meteorological Applications* 14 (2007): 263-273.

Ng, E., L. Chen, Y. Wang, and C. Yuan. "A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. *Building and Environment* 47 (2012): 256-271.

Nielsen, Morten. "Turbulent ventilation of a street canyon." *Environmental Monitoring and Assessment* 65 (2000): 389-396.

Oke, T. R. "Urban heat islands," in *The Routledge Handbook of Urban Ecology*, edited by Ian Douglas, David Goode, Mike Houck and Rusong Wang, 120-31. Abingdon, Oxon: Routledge, 2011.

Oliveira, S., H. Andrade, and T. Vaz. "The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon," *Building and Environment* 46 (2011): 2186-2194.

Pearlmutter and Kruger. "The effect of urban evaporation on building energy demand in an arid environment. *Energy and Buildings* 40 (2008): 2090-2098.

Pigeon, G., D. Legain, P. Durand, and V. Mason. "Anthropogenic heat release in an old European agglomeration," *International Journal of Climatology* 27 (2007): 1969-1981.

Pompeii II, William C., and Timothy W. Hawkins. "Assessing the impact of green roofs on urban heat island mitigation: A hardware scale modeling approach," *Geographical Bulletin* 52 (2011): 52-61.

Ratti, Carlo and Paul Richens. "Raster analysis of urban form," *Planning and Design* 31 (2004): 297-309.

Ratti, C., S. Di Sabatino, and R. Britter. "Urban texture analysis with image processing techniques: wind and dispersion," *Theoretical and Applied Climatology* 84 (2006): 77-90.

Rozenweig, C., W. Solecki, L. Parshall, B. Lynn, J. Cox, R. Goldberg, S. Hodges, S. Gaffin, R. Slosberg, P. Savio, F. Dunstan, and M. Watson. "Mitigating New York City's heat island: Integrating stakeholder perspectives and scientific evaluation." *American Meteorological Society* 90 (2009): 1297-312.

Saito, I., O. Ishihara, T. Katayama. "Study of the effect of green areas on the thermal environment in an urban area," *Energy and Buildings* 15-16 (1990/91): 493-498.

Spronken-Smith, R.A. and Tim Oke. "Scale modeling of nocturnal cooling in urban parks," *Boundary-Layer Meteorology 93* (1999): 287-312.

Stone, B., and J.M. Norman. "Land use planning and surface heat island formation: A parcel-based radiation flux approach," *Atmospheric Environment* 40 (2006): 3561-3573.

Swedish Commission on Climate and Vulnerability. "Sweden facing climate – threats and opportunities." Stockholm: 2007.
http://www.sweden.gov.se/content/1/c6/09/60/02/56302ee7.pdf (accessed January 2012).

Unger, Janos. "Intra-urban relationship between surface geometry and urban heat island: review and new approach," *Climate Research* 27 (2004): 253-64.

The University of Copenhagen in partnership with DHI and GRAS ."Urban Heat Island in Copenhagen," Presented to Copenhagen's Center for Park and Nature, July 2010.

Watkins, R. "The impact of the urban environment on the energy used for cooling buildings." PhD thesis, Brunel University, 2002.