UNIVERSITY OF GRONINGEN

Adapting to urban heat in the 21st century

Lessons from the Phoenix and Dubai for north-western Europe

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August, 2019

SUMMARY

This thesis investigates the strategies that Dubai and Phoenix employ to mitigate the urban heat island effect. The aim of the thesis is to assess whether Groningen might be able to learn anything from Dubai and Phoenix. As the earth is warming, more cities are subjected to extreme heat. Cities absorb more solar radiation than rural areas, because they typically have more impervious surfaces, heat absorbing materials, and less vegetation. Climate change will lead to more intense urban heat islands because of more frequent and longer lasting heat waves**.** This in turn leads to higher mortality and morbidity rates, and lower worker productivity. Extreme heat causes disruptions to road and rail, and mobile networks. Because the built environment of cities in moderate climates is insufficiently capable of dealing with extreme heat, cities should look at cities with longstanding traditions of dealing with heat.

The thesis first investigates the reason why urban centres warm up more than the countryside. Second, the causes of the UHI are linked to adaptation strategies which cities can use to counter the urban heat island. The strategies of Dubai and Phoenix and Groningen are compiled using policy documents, newspaper articles and observations from satellite and 3D imagery. A comparison is made between Groningen and the two case-cities.

All three cities use greening measures to provide a cooler city climate. However, the object of Phoenix and Dubai also promote reflective roofs, densification, improved building orientation, shading canopies, courtyards, wind towers and misting fans. Their applicability to the case of Groningen was assessed using three typologies made for the hotspots of Groningen; a) commercial areas, b) city squares and open areas, and c) highly urbanized areas. Some of the adaptation strategies may be less suited to Groningen, because it has colder winters when receiving more solar energy is desired. Instead, temporary installations may provide the city with cooling during summer.

The use of reflective roofs can decrease air temperatures in the city and reduce the cooling load in buildings. This decreases the anthropogenic heat release, decreasing the urban heat island effect. Currently, very few buildings in Groningen use cool roof technologies. Exposing fewer surfaces to solar radiation through densification or by enhancing building orientation may further contribute to lower temperatures in the city. Dubai and Phoenix use artificial shading devices, which can be equipped with solar panels. These can serve as carports, or the solar panels can serve as a second skin above houses. Reflective and green roofs without solar panels are more efficient at reducing air temperatures. Courtyards are presented as a viable adaptation strategy in the Netherlands, based on existing literature. Wind towers have found their way into southern Europe, but are not yet used in north-western Europe. They are expected to have potential in moderate climates. Testing grounds or art installations of wind towers in Groningen can help aid in the exploration of the potential of wind towers. Misting fans can provide heat relief during heat waves, but their effect on the UHI is unclear. In conclusion, Groningen can learn a lot, concerning Urban Heat Island strategies from the American South-west and the Middle East.

Cover picture: *Souk Madinat Jumeirah*, Bill Drives, 2017

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Glossary

Adaptation Strategy:

Throughout this thesis, adaptation strategies refer to adaptation strategies aimed at diminishing the harmful effects of the urban heat island (UHI). A broad definition of adaptation strategies is given by Niang-Diop and Bosch (2005).

> *"A general plan of action for addressing the impacts of climate change, including climate variability and extremes. It will include a mix of policies and measures with the overarching objective of reducing the [region's] vulnerability. Depending on the circumstances the strategy can be comprehensive at a national level, addressing adaptation across sectors, regions and vulnerable populations, or it can be more limited, focusing on just one or two sectors or regions"*
>
> (Niang-Diop and Bosch, 2005, p. 186)

Advection: Advection is defined as the transport of air and moisture, or wind.

Convection: Convection is here defined as the heat transfer from the soil or an object to the air, often causing a low pressure area, due to rising thermals. The rising air can create advective wind flows.

SVF: Sky View Factor: A ratio at a point in space between the visible sky and a hemisphere centred over the analyzed location (Oke 1981). It is a number in between 1 and 0, where 1 signifies an open sky in a flat open field.

UCI: Urban Cool Island: The difference in temperature between the rural area and the nearby urban area when the urban area is cooler.

UHI: Urban Heat Island: The difference in air temperature between the rural area and the nearby urban area when the urban area is hotter.

SUHI: Surface Urban Heat Island: The difference in surface temperature between the rural area and the nearby urban area when the urban area is hotter.

UCL: Urban Canopy Layer: The microscale layer reaching up from the street level to the average building height. The area in which pedestrians are present.

UBL: Urban Boundary Layer: The meso-scale layer reaching up from the top of the average roof height to the planetary boundary layer.

1. Introduction

1.1 Climate change and heat in the city

Global temperatures are on the rise and we may reach an average increase of 1.5 degrees °C within the next 20 years (IPCC, 2018). Even if warming can be kept below the 2 °C target set by the Paris Agreement, droughts and deadly heat waves are likely to become more frequent and intense (Matthews et al. 2017; Zhao *et al.* 2018). They will span larger areas, and last longer (Meehl and Tebaldi, 2004, in Wouters et al., 2017). Cities are already warmer than the countryside due to a phenomenon called the urban heat island effect (UHI). The difference in temperature is the related to a lack of trees and vegetation, and a large fraction of impervious surfaces. Climate change is likely to increase the intensity of the urban heat island effect, mostly due to an increase in heatwave conditions (Gabriel & Endlicher, 2011, Li & Bou-Zeid 2013; Founda & Santamouris 2017; Zhao *et al.* 2018). Heat stress is expected to be twice as high in big cities compared to rural areas (Wouters et al., 2014).

As the earth warms, urbanization trends continue. According to the United Nations (2014, in Hintz, Luederitz, Lang, & von Wehrden, 2018) it is likely that two thirds of the world population will live in cities by 2050. As a result, a higher fraction of the world population will also be subjected to the urban heat island and heat stress. Mora et al. (2017) predict that by 2100 around 48 percent of the world population will be exposed to deadly heat for at least 20 days a year. When no drastic actions are taken to reduce emissions, this number is expected to increase to 78 percent. A heatwave in 2003 claimed 70.000 lives across continental Europe, proving how deadly heatwaves can be (Lee et al., in Hanna and Tait, 2015). Most of these deaths occurred in cities (Garcia-Herrera et al., 2010). According to Beniston, (2004, in Gabriel & Endlicher, 2011) conditions similar to the ones of the summer of 2003 may become normal at the end of this century.

Extreme heat is the number one most lethal weather-related disaster in the United States (Harlan and Ruddell 2011) and Larssen (2015) states that this statistic holds true for the world as a whole. On top of being deadly, heat can cause a range of uncomfortable afflictions. It can cause headaches, nausea, irritability and dizziness (Hanna and Tait 2015). It can also cause confusion, cramps and shortness of breath (Ibid.). The heat is detrimental to worker productivity, impairing risk assessment and planning (Ibid.). Furthermore, extreme heat can lead to power outages, due to increased demand for cooling in industrial facilities and homes. Extreme heat can also cause tarmac to melt, and prevent bridges and cell phones from working. The urban heat island can also lead to the formation of smog over cities, lowering the air quality.

The problem is already widely acknowledged, and many countries and cities have developed adaptation plans to counter the harmful effects of climate change. For example, they target a change in land-use or they implement heat warning systems (Harlan and Ruddell 2011; Gabriel & Endlicher, 2011). However, heat warning systems are a short-term solution. Long term adaptation measures should focus on improving urban planning and building design (Gabriel & Endlicher, 2011). This could be done by looking at building practices from around the world. The World Health Organization also states that the effects of climate change on health are exacerbated by poor urban design (Akbari *et al.* 2015). Buildings that were designed for specific thermal conditions will have to perform in hotter and drier climates (Ibid.).

Van den Dobbelsteen (2019) writes that cities from colder climates could learn a lot from those already dealing with much higher temperatures. . In the case of the Netherlands, conventional construction and design methods have proven unable to provide sufficient cooling for vulnerable populations (Heusinkveld *et al.* 2014). Consequently, the Netherlands is one of the countries which may benefit from looking at heat-adaptation strategies from hot climates. A potential reason why cities are not yet learning from warmer cities, is the information-transfer gap between academics and urban planners and architects (Dubois et al., 2012). Klok and Kluck (2018) state that Dutch planners often lack the proper understanding of heat risks and how to incorporate heat related adaptation strategies into urban planning. Like Van den Dobbelsteen, they suggest that this understanding can be improved by looking at and learning from cities in other (warmer) climatic regions that already have been adapted to heat.

Bridging this information gap could then be achieved by presenting the adaptation strategies from a city-perspective. Much of the literature focuses on individual adaptation strategies, and does not link it to the transferability to colder climates (Observation, 2019). Rather, they discuss the benefits in situ. As a result, the adaptation literature is rather diffuse. This may be one of the reasons why architects and urban planners have difficulty adopting these strategies. This thesis aims to present a comprehensive adaptation measures from warmer climates from a city-perspective -as suggested by Van den Dobbelsteen, Klok and Kluck, and makes the link to their applicability in the Netherlands.

Interestingly, much of modern architecture in the Middle East has been criticized for neglecting vernacular design principles, relying on energy consuming air conditioning to cool spaces (Benslimane & Biara, 2019; Eiraji & Namdar, 2011; Morad & Ismail, 2017; Shabahang, Vale, & Gjerde, 2019). A return to traditional architectural elements can be observed, because of their advantages to indoor and outdoor climate (Eiraji & Namdar, 2011). This shows that even cities in warmer climates are drawing lessons from their past.

1.2. The research question

This master thesis aims to look at adaptation strategies from two regions which have been dealing extreme heat for decades, and their applicability to a north-western European setting. For this research, Groningen (maritime temperate climate) was taken as the main case. Dubai (hot desert climate) and Phoenix (hot desert climate) have been chosen as the cities from which to learn. Both have developed strategies to lower the urban heat island.

The following research question has been formulated:

"What are the evidence-based adaptation strategies used in Phoenix and Dubai to counter the urban heat island, and can they be applied to Groningen?"

A comparative research strategy is used to answer the following research questions:

Objective 1 – What causes *the urban heat island effect?*
Objective 2 – *Which adaptation strategies exist and which process do they target?*
Objective 3 – *What strategies do Groningen, Dubai, and Phoenix employ to counteract the urban heat island effect?*
Objective 4 – *Which strategies from Dubai and Phoenix are useful for Groningen to lower the urban heat island effect?*

The aim of this research is to find adaptation strategies and urban design strategies which are most effective at limiting the urban heat island. Heat stress may be underestimated by the city of

Groningen. To support this statement, the Dutch Planning Bureau for the Built Environment writes that the Netherlands is a well-organized country, but that its mind-set lingers in the 'old climate' (Planbureau voor de Leefomgeving, 2015). The same may be true for the range of adaptation options it considers. An important facet of this research is therefore the effect of climate change on the intensity of the urban heat island and the climate of Groningen. What are the conditions Groningen will deal with in 2050?

The thesis follows the same structure as the research questions. It first investigates the causes of the UHI in chapter 2.1. Chapter 2.2 discusses the adaptation strategies, and their corresponding adaptation measures which can be employed to lower the urban heat island. The adaptation strategies are merged into a conceptual model, which describes how a city might counteract the urban heat island. The conceptual model is the guiding tool which allows for the systematic review of the three cities using a case study. The case study design is discussed in the methodology chapter, chapter 3. The results and findings can be found in chapter 4, linking the causes of the UHI in Phoenix and Dubai to their adaptation strategies. Chapter 5 makes a comparison between Groningen and the two case-cities, and assesses the applicability of adaptation strategies from Dubai and Phoenix to Groningen. Finally, chapter 6 briefly answers the research questions in a conclusion. The final paragraph reflects on the research process, and makes suggestions for future research.

2. The urban heat island and its remedies

In order to understand how Dubai and Phoenix work towards a cooler, liveable city, it is necessary to fully understand the mechanisms which warm or cool the city. This chapter first investigates the causes of the urban heat island and the mechanisms at work in chapter 2.1. Chapter 2.2 lays out the broader strategies to counter the UHI, and the planning actions or adaptation measures used to implement them. The chapter is concluded in chapter 2.4 by a conceptual framework.

2.1 Urban heat island

2.1.1 The causes of the urban heat island

The urban heat island is a well-studied phenomenon. The urban-rural temperature difference was first observed by Luke Howard in London, in 1833. Since then, the body of literature on the urban heat island has expanded enormously. Temperatures in the city can be an average of 3°C warmer compared to the countryside, but temperature differences exceeding 10°C have been reported (Basagaña, 2019). This is often the case during heatwaves or when anticyclonic summer weather conditions are in place. At times like these, solar radiation is at its peak and wind speeds are low, limiting the cooling potential (Heaviside, Cai, & Vardoulakis, 2015). The relatively higher temperatures are the result of changes in land use, urban geometry and surface roughness (Gunawardena *et al.* 2017). These modifications to the built environment influence the city climate through five different factors (Ramamurthy & Bou-Zeid, 2017). The factors are: climatology, thermal storage, evaporative cooling, advective cooling and anthropogenic heat.

1) **Climatology**: First and foremost, the regional climate has a large effect on the urban heat island. The latitude, elevation and topography of cities all impact the solar radiation they receive, but are also an important determinant of the moisture present in an area (Basagaña, 2019). For example, cities close to large water bodies may benefit from a cooling sea breeze (Vahmani & Ban-Weiss, 2016, in Ramamurthy & Bou-Zeid 2017).

2) **Thermal storage**: Cities act like heat sinks due to a variety of factors. Firstly, they have a lot of vertical faces capable of storing heat. Secondly, these walls and facades are often made of concrete or brick, which are capable of storing more heat than natural surfaces such as trees, grass or soil (Ryu & Baik, 2012). The albedo of such materials is often higher than those of natural materials. Albedo is the fraction of radiation which is reflected back to the source. The albedo of an urban area averages around 0.15 (Taha, 1997), which means they absorb 85 percent of the total radiation. Lightly coloured materials often have a higher albedo and transfer less heat into the atmosphere (Chapter 2.3.1). According to Hove (2011) cities are capable of storing twice as much heat as rural areas during the day. A part of the heat that is stored during the day radiates back into the atmosphere at night, causing higher ambient temperatures at night (Ramamurthy et al., 2014, in Ramamurty & Bou-Zeid, 2017). A third factor of thermal storage, which contributes to the increased UHI, is radiative trapping. Shortwave radiation is reflected multiple times in an urban environment and consequently warms more surfaces. This effectively lowers a city's albedo (Ryu & Baik, 2012). Lastly, the reduced skyview factor in cities reduces the outgoing longwave radiation. The sky view factor (SVF) is a number one a scale of 0 to 1 which signifies the extent to which the sky is exposed. A SVF of 0 means the entire sky is obstructed from view, whereas a SVF of 1 would be found in a flat, open field. A larger SVF means stored heat is radiated back into the sky more easily.

3) **Evaporative cooling**: The potential for evaporative cooling is limited by the cities' built-up surface fraction and impervious surface cover. The lack of trees and other forms of vegetation cause more radiation to be converted into sensible heat instead of latent heat (Sailor, 2008, in Ramamurthy and Bou-Zeid, 2017). In other words, energy which would otherwise heat up the air is now used for the evaporation of moisture.

4) **Advective cooling**: Advective cooling is diminished in cities, because heat dissipates less easily. Buildings obstruct the flow of wind and slow it down. The surface roughness in cities is generally lower in cities, which reduces vertical mixing. However, differences in air pressure between the warmer city and cooler countryside induce airflows that suck in cool air from outside of the city. This can have a moderating effect on urban air temperature (Haeger-Eugensson & Holmer, 1999, in Ramamurthy and Bou-zeid, 2017).

5) **Anthropogenic heat**: Anthropogenic heat released into the atmosphere is the residual of energy used for space-heating, cooling equipment and for vehicles (Taha, 1997, in Ramamurthy & Bou-zeid, 2017). The magnitude depends on the intensity of power generation and the types of transportation systems in place.

Table 1 gives an overview of the individual components responsible for the UHI.

Climatology
Solar radiation
Ocean breeze
Increased Thermal Storage
-Large vertical faces
-Reduced sky view factor Increased absorption of shortwave radiation Decreased long-wave radiation loss Decreased total turbulent heat transport -
Surface materials Thermal Properties Higher heat capacities Higher conductivity Increased surface heat storage
Reduced Evaporative cooling
Larger Impervious surface area Shed water more quickly Increased runoff with rapid peak discharge Decreased evapotranspiration
Reduced Advective cooling
Decreased total turbulent heat transport due to lower surface roughness
3D geometry of buildings – canyon geometry
Anthropogenic heat
Electricity and combustion of fossil fuels Heating and cooling systems Machinery Vehicles Air Pollution Increased longwave radiation from the sky Greater absorption and re-emission

Adapted from: Ramamurthy and Bouzeid, 2017;Grimmond, 2007

Table 1: Causes of the urban heat island

2.1.2 The scales of the urban heat island

The urban heat island is a phenomenon that occurs three scales. The urban canopy layer (UCL) at the micro scale is most relevant for daily life, since it is occupied by pedestrians (See figure 1). It stretches in between street level and the average height of housing. The sky view factor and H/W factors are important factors in the total radiation that is received (Gunawardena et al., 2017). Both are discussed in chapter 2.3.1. Different neighbourhoods can have different climates depending on their land use and topography. They are included in the local scale of the UHI. Main determinants are the size and spacing of buildings (Hove et al., 2011). The urban boundary layer (UBL) extends up to a

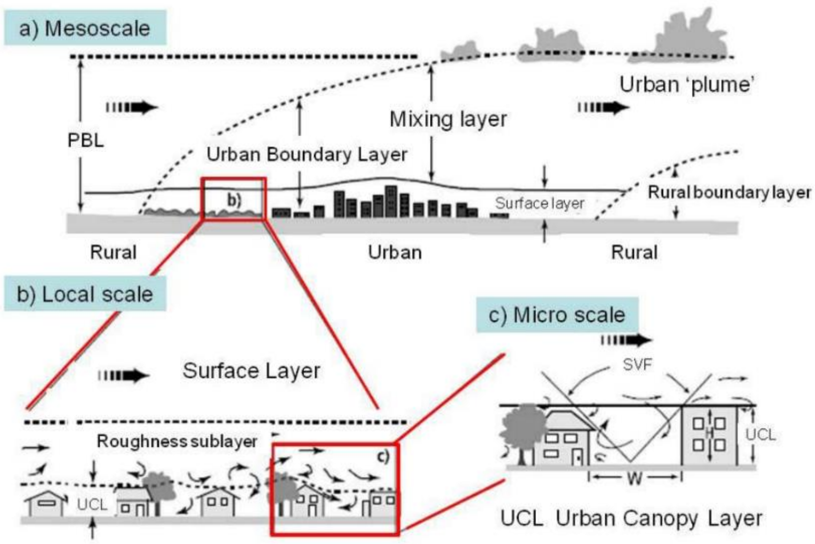


Figure 1: The scales of the urban heat island (Hove et al., 2011, p. 14)

few kilometres above the city. The UBL is a meso-scale phenomenon and can be regarded as the city climate. Lower temperatures at the microscale translate to lower temperatures at the mesoscale. When referring to the UHI, this thesis refers to the UCL, unless specified otherwise.

2.1.3 The urban heat island and thermal comfort

While the urban heat island is the object of study, thermal comfort remains an important consideration. Some scholars argue human comfort is more important than the UHI itself (Budd, 2008, in Steeneveld et al., 2011). Where the UHI is only an indicator of a temperature gradient, thermal comfort links temperature to human health. Any measure that is aimed at lowering the urban heat island, also improves human health by enhancing thermal comfort. When temperatures are within a comfortable range, morbidity and mortality rates are lower.

Thermal comfort is influenced by humidity, air temperature and air movement, as well as by age, clothing, activity level and mean radiant temperature (Emmanuel & Fernando, 2007). Mean radiant temperature is the temperature emitted by surfaces in the direct vicinity of a person. Because air temperature, air movement and mean radiant temperature are largely dependent on urban design measures, they are intrinsically linked to heat adaptation strategies and the urban heat island. Age, clothing, and activity level are not linked to the urban heat island, but are related to social adaptation strategies, which are outside the scope of this thesis.

Thermal comfort is considered a key aspect of environmental quality. The International Organization for Standardisation defines thermal comfort as "the condition of mind which expresses satisfaction with the thermal environment" (1994, in Emmanuel & Fernando, 2007). Which thermal ranges are 'satisfactory' differs per country and per person, and therefore impossible to generalize. Populations in hot and arid regions have adapted their bodies to the heat, which explains why average temperatures of 35°C are much more deadly in moderate climates.

To illustrate, Huynen et al. (2001, in Daanen et al., 2010) found that a temperature of 16.5°C results in the fewest heat related deaths in the Netherlands. Conversely, in Bangkok, Thailand the optimal temperature is 29°C (Hanna & Tait, 2015). Mora et al. (2017, p. 501) writes that "given the speed of climatic changes and numerous physiological constraints, it is unlikely that human physiology will evolve the necessary heat tolerance". Hanna and Tait (2015) furthermore note that acclimatization alone will not be able to overcome the higher temperatures resulting from climate change. This is why the implementation of urban adaptation strategies is so important.

From an urban planning and governance perspective, it is arguably easier to influence the physical domain than the social domain. Governments can't dictate activity, or clothing level, or even the age of city residents. Rather, they can make an effort to ensure that the baseline temperature is as low ass possible. Including thermal comfort in the research question would mandate the inclusion of social policies, but these don't contribute to lower temperatures in the city.

2.2 Adaptation strategies to counter the UHI

Spatial planning and urban governance are of key importance in mitigation and adaptation of the harmful effects of urban heatwaves (Bicknell et al., 2009, in Hintz et al., 2018). Adaptation strategies can be defined as

"*… a general plan of action for addressing the impacts of climate change, including climate variability and extremes. It will include a mix of policies and measures with the overarching objective of reducing the [region's] vulnerability. Depending on the circumstances the strategy can be comprehensive at a national level, addressing adaptation across sectors, regions and vulnerable populations, or it can be more limited, focusing on just one or two sectors or regions*"

(Niang-Diop and Bosch, 2005, p. 186)

The adaptation strategies addressed in this thesis aim to limit the climate extremes which are caused by the urban heat island in conjunction with climate change. The vulnerability of a region, in this case the city, is reduced by lowering the exposure to heat. Vulnerability is a combination of exposure, sensitivity and adaptive capacity. The same categorization is used by the IPCC in its various forms of reports (IPCC, 2007, in Leal Filho et al., 2018). As discussed in 2.2, reducing human sensitivity in such a short time span is seen as a strategy with limited chances of success. Adaptive capacity is also not the subject of this thesis. The adaptation strategies have been categorized in order to match the five causes of the UHI, minus the climatological factors. Climatological factors, such as geographical location cannot be altered. Instead, climatic conditions can be exploited by the other four strategies. For this reason, climate does not have its own place in the adaptation strategy chapter.

Table 2: Adaptation strategies to the urban heat island (Adapted from Grimmond, 2007)

Decreasing the thermal load	**Increasing the evaporative potential**	**Increasing the advective cooling potential**	**Reducing output and storage of anthropogenic heat**
Reflective materials	Greenspace Trees and parks	Generating wind flows	Reduced solar loading internally
Heat storing materials	Green roofs	Variability of building heights	District heating and cooling
Optimizing the spacing between buildings	Green walls	Urban ventilation corridors	
Optimizing building orientation	Permeable pavements		
	Waterbodies and fountains		

2.2.1 Decreasing the Thermal Storage Capacity – Materials & Shading

Cities act like giant heat sinks due to the properties of many of the materials they are constructed with. Cities are also characterized by higher buildings, resulting in a larger total area which receives sunlight. The materials they are constructed with have higher heat capacities and conductivities, which lead to higher surface and ambient air temperatures. The implementation of cool pavements or limiting the area of vertical surfaces exposed to radiation are two strategies that can be employed to counter the UHI. They are discussed more in-depth below. Porous pavements, which could be considered as a cool pavement are discussed in chapter 2.3.2, because they rely on evaporation.

Cool pavements & materials

Urbanization often results in a decrease in surface albedo. Natural land cover is replaced by darker and denser materials, which reflect less short-wave radiation and continue to emit long wave radiation after sundown (Zhou et al., 2014). ‘Cool’ materials are aimed at countering this. They employ different methods of lowering their surface temperatures. They either stay cool by reflecting more energy back into the troposphere, or they store heat differently (Qin, 2015). Both types are discussed below.

Reflective materials

Different kinds of reflective materials exist. They can reflect visible light, or just the infrared part to prevent any unwanted glare. By improving the albedo, more solar radiation is reflected back into the atmosphere. Surfaces with low absorption also reduce heat conduction into buildings and to lower ambient air temperatures, which result in less heat penetration and infiltration into the building. As such, replacing dark and dense fabrics with reflective and ‘cool’ materials can help alleviate the urban heat island (Levinson and Akbari, 2010, in Botham-Myint et al., 2015). An example of an adaptation strategy would be the implementation of cool roofs roofs (Figure 2). Cool

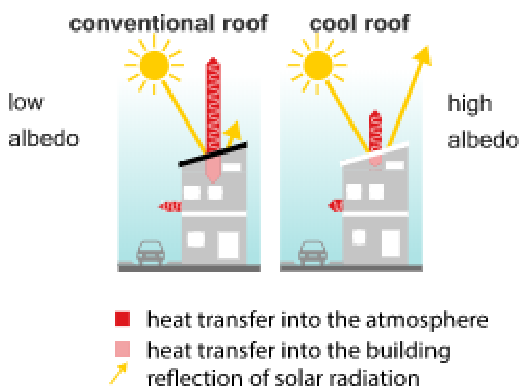


Figure 2: The workings of a cool roof (Deutscher Wetterdienst, 2019)

roofs can reduce the air temperature by up to 1°C and the peak air temperature by 2.5 (Santamouris, 2014a, in Kyriakodis & Santamouris, 2018).

A large cool paving project in Greece achieved a reduction in air temperatures of 1.5 degrees Celsius, and a maximum surface temperature reduction of up to 11.5 degrees Celsius (Kyriakodis & Santamouris, 2018). Conventional asphalt was replaced by a thin layer of light yellow asphalt, changing the albedo from 0.04 to 0.35. Botham-Myint et al. found that temperatures can be up to 3°C cooler in neighbourhoods with cool roofs.

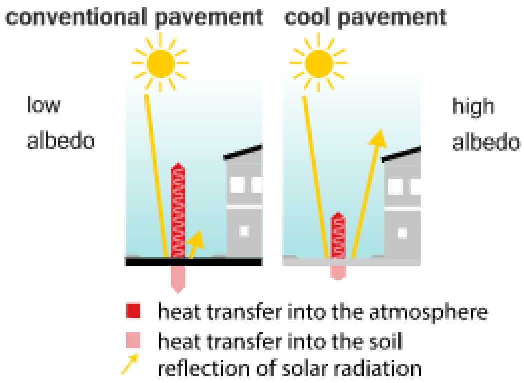


Figure 3: The workings of a cool pavement (Deutscher Wetterdienst, 2019)

A large benefit of reflective materials is that they can be employed on almost all urban surfaces, such as pavements, roofs and even walls (Figure 3. In order to prevent unwanted glare, materials have been developed which do not reflect visible light, but only infrared radiation. Regular reflective material is especially effective in open spaces, where the infrared heat isn't reflected back towards buildings (Ibid.).

This is also illustrated by a study by Yang et al. (2013, in Sen & Roesler, 2014) who state that when radiation is reflected towards buildings, a higher albedo isn't necessarily beneficial to a city. During winter it can lead to higher heating costs, and due to reflected shortwave solar radiation in summer, lead to higher cooling costs in summer. The higher cooling costs in summer could be prevented by the use of retroflective materials. Retroflective materials reflect sunlight straight back at the source, usually the sun.

Another potential drawback of reflective roofs with a high albedo is that they reduce rainfall (Yang et al., 2015). Less humid air rises to form clouds, which ultimately leads to less precipitation. Lower soil moisture contributes to a larger UHI through reduced evapotranspiration. Yang et al. (2015) show a 4% decrease in the total accumulated precipitation in the Arizona Sun Corridor in a maximum expansion scenario combined with reflective roofs.

Another point that has to be made is that while the project in Greece did improve thermal comfort, a study in New York reveals that thermal comfort isn't significantly increased by using reflective pavements (Lynn et al., 2009, in Yang et al., 2015). The solar radiation is reflected towards pedestrians, and the heat flux emitted by the ground doesn't really change. This is different for heat storing materials, which 'feel' cooler. Cool roofs on high-rise do not have any direct benefit for thermal comfort at pedestrian level either, but do contribute to a significantly cooler UBL (Botham-Myint et al., 2015).

Heat storing materials

Many different materials are being developed, among which are heat-harvesting systems, phase changing materials and thermochromic coatings. Heat-harvesting systems or pavements convert solar radiation to renewable energy using solar collectors and a piping system connected to a heat exchanger (Qin, 2015). As a result, surface temperatures remain lower. Phase changing materials transfer solar radiation to latent heat, also effectively lowering surface temperatures by up to 8 K (Ibid). High conductive materials have a large thermal capacity and stay cooler during the day, but may be warmer at night when they continue to emit longwave radiation (Ibid.). Thermochromic coatings can have the benefit of reflecting more heat when it's hot (in summer) and less when it's cold (in winter) by changing colour accordingly (Ibid). This is beneficial for regions with less sunlight in winter.

Optimizing the spacing between buildings

A wide street is often hotter during the day than a narrow street with tall buildings (Oke et al., 1991, in Johansson & Emmanuel, 2006; Arnfield, 2003, in Johansson & Emmanuel, 2006). At night however, the roles reverse. The narrow street offers shade during the day and is relatively cool (Figure 4), but is prevented from cooling down at night due to its small sky view factor. Streets with a high sky view factor cool down more easily, because long wave radiation is unobstructed by buildings. Hence, narrow streets and alleys stay warm at night, but are cooler during the day. Urban cool islands (UCI) can form during the day, because of the shading they provide and their high thermal capacity (Basagaña, 2019). Deep urban canyons and UCIs are often found in hot and humid regions Al-Sallal and Al-Rais (2011).

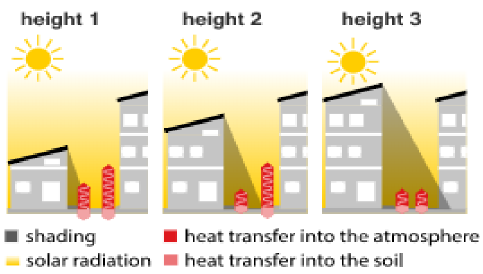


Figure 4: Canyon width and shading (Deutscher Wetterdienst, 2019)

Johannson and Emmanuel (2006) suggest that a higher nocturnal UHI, is less of a problem in commercial areas than in residential areas, which is why a small SVF is favourable here. Memon et al. (2010) found that nocturnal UHI in areas with a high height to width (H/W) ratio of 8 can be as much as 7.5°C warmer than those with a lower ratio of 0.5. H/W ratios are another way of quantifying urban canyon geometry. Wide streets with low buildings have a lower H/W ratio, whereas narrow streets flanked by tall buildings have a higher ratio.

Optimising Building Orientation

In addition to the width of streets, their orientation plays a large role in the total radiation they receive. Chatzipoulka et al. (2016) demonstrate this by comparing different urban forms with a similar density but with a different geometry and layout, showing that a particular configuration received more than 32% radiation on the ground and 11% more radiation on façades. Grimmond and Oke (2002) note that the uptake of heat is largest just before noon when solar radiation reaches its peak. Shading by buildings is most important during these hours.

This is also illustrtated by a report written by Mohajeri et al. (2019) who investigated the effects of canyon geometry on solar access for the city of Geneva. They find that streets oriented WNE-ESE receive the most radiation. This is because they have the largest number of houses facing SSW. A theoretical study of radiation gain in the Netherlands yielded a similar outcome, demonstrating that E-W oriented streets receive more solar radiation than N-S oriented streets (Van Esch et al., 2012, in Mohajeri et al., 2019). This is due to the shortwave radiation that is reflected multiple times within the urban canyon. Because both Geneva and the Netherlands receive relatively little radiation in winter, a dilemma arises. To maximize thermal comfort for pedestrians in summer, minimum solar gain is preferable, while the opposite is true for winter (Mohajeri et al, 2019).

Chatzipoulka et al. (2016) write that a better understanding of the interplay between solar gain, solar altitude angles and urban geometry can lead to opportunities for more effective and climate sensitive solar urban design. The optimal arrangement and orientation of buildings differ per place, because the maximum angle of the sun differ too. In subtropical latitudes the orientation of wide streets is of hardly any influence on ambient air temperatures (Ali-Toudert & Mayer, 2004). Here, streets oriented E-W near the equator hardly benefit from any shade due to the sharp angle of solar radiation, whereas streets oriented N-S do benefit from shade in the early morning and afternoon (ibid). Ali-Toudert and Mayer (2004) write that NE-SW and NW-SE streets lead to the better thermal comfort than E-W streets because the street is always partly shaded.

2.2.2 Increasing evaporative cooling potential – Urban Greening and Waterbodies

Another important adaptation strategy to counter the UHI is increasing the potential for evapotranspiration. Evaporation is the combined sum of evaporation and transpiration from plants. Water in the city is usually transported downstream as fast as possible, disappearing in sewers or flowing into a larger stream or river (Grimmond, 2007). Consequently, less surface water remains for evapotranspiration, negatively affecting the urban surface energy balance (Taha, 1997). Retaining water in the urban environment means more radiation can be absorbed by a latent heat flux instead of being converted to a sensible heat flux, reducing air temperatures. Two methods which rely on this principle are greening and the replacement of impervious surfaces with permeable pavements. The key in this is retaining moisture in the urban environment. The mechanisms at work and their effectiveness are discussed below.

Greenspace

Increasing the share of greenspace in a city can greatly improve thermal comfort in cities, and contributes to lower temperatures through various mechanisms (Anniballe et al., 2014). Alongside evapotranspiration trees and plants also provide shade, and can positively impact wind velocity and direction (Lindberg & Grimmond, 2011). Armson et al. (2012) estimated that trees in rural areas can reflect up to around twenty-five percent of the incoming shortwave radiation back to the atmosphere. Grass was found to have a lower performance, reflecting back 15 percent of the radiation (Ibid.). An increase in vegetation also adds to the urban roughness and enhances convective cooling, with less stagnant air as a result (Loehrlein, 2013). The advective and convective cooling potential will be discussed here alongside evapotranspiration, but also briefly in chapter 2.2.3. Additionally vegetation sequestrates carbon, capture particulate matter and dust, and filters noise (Lindberg & Grimmond, 2011).

Evapotranspiration is an especially effective method of countering heat stress in warm and dry climates. Taha (1997) writes that evapotranspiration can create cool islands which are up to 8°C cooler than the surrounding areas. Grass on sport fields have shown to cool air by 1.1°C up to 2.2°C compared to the area bordering them (Loehrlein, 2013). Emmanuel and Loconsole (2015, in Gunawardena et al., 2017) found that a 20% increase in greenspace in the city of Glasgow could help to lower the intensity of its 2050 UHI effect by 33 to 50 percent.

The cooling potential of vegetation was also modeled for the cities of Washington D.C. and Baltimore during a heatwave by Loughner et al. (2012). They investigated the effects of greening the urban space of both cities with a 50 percent tree cover over urban roads, and a 10 percent decrease in the width of roads to make room for soil and grass. They found an average air temperature reduction in street canyons of 4.1°C, and a reduction of street surface temperature of 15.4°C. Finally, a reduction of 8.9°C was found in façade surface temperatures. The cooling was the combined result of tree shading and evapotranspiration. The convective and advective cooling was not taken into account, but these could lower temperatures even more. At night, trees can trap heat when they are located close together. A street which has intermittent spacing in between the trees will cool down at night, because its surfaces can emit the stored heat towards the night sky (Coutts et al., 2016).

Trees and Parks

In addition to greening streets, clustering vegetation is also beneficial. A tree grove can have air temperatures which are up to 5℃ lower than air temperatures in open terrain (Loehrlein, 2013). Mature trees providing shade in a suburban area provided up to 3.3℃ cooling to air temperatures compared to newer suburbs (Ibid.). Shaded areas under trees can be as much as 13.9 degrees cooler at midday, according to Loehrlein (2013). Vidrih and Medved (2013, in Gunawardena et al., 2017) found that networks of smaller greenspaces of 0.2 to 0.3 square kilometers are capable of providing an effective distribution across a city. In order for a green area to provide significant cooling effects, it has to span an area larger than 50 square meters (Doick and Hutchings, 2013, in Gunawardena et al., 2017). Figure 5 gives an example of green space in the city.

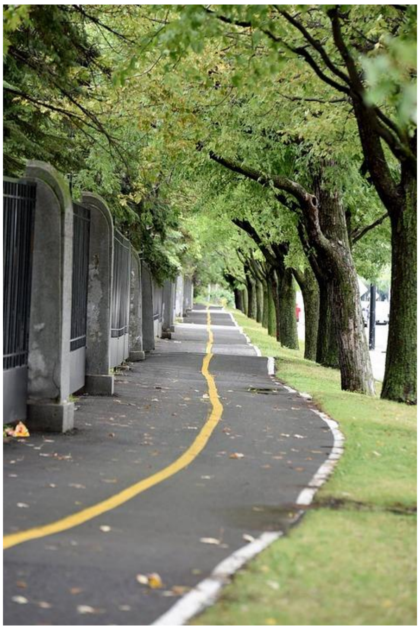


Figure 5 Urban Greening Along a Bicycle Path, Montréal (Furaxe, 2017)

Heat is trapped in the upper one third of the crown of a tree, which illustrates that especially tree size is important, and therefore type and age (Ibid). Transpiration potential largely relies on crown area, leaf area index, the height of the leaves above the ground level, and water content and availability, as well as a few others (Armson et al., 2012, in Gunawardena et al., 2017).

Different species of plants have different cooling potentials, which also differ along a temporal axis (Gunawardena et al., 2017). For example, trees native to cool and wet climates which have a metabolism classified as 'C3 photosynthetic' open their leaf pores during the day, transpiring large quantities of moisture. Contrarily, plans originally from warmer and drier climates have a C4 photosynthetic metabolism which causes them to retain water during the day, and to open their pores at night. This effectively lowers their cooling potential to reduce the UHI during the day (Doick et al., 2014, in Gunawardena et al, 2017). Trees which thrive well in more southern regions of Europe may be able to do so as well in the Netherlands, but their cooling potential is much lower. Increasing the tree diversity in an area helps contribute to an increased urban roughness, increasing vertical mixing.

The importance of trees and other greenery as an adaptation strategy is becoming larger, but they also have to deal with the growing burdens of climate change, especially heat and droughts in summer (Roloff et al., 2009, in Larssen, 2015). Undoubtedly, the health and diversity of the plants and trees are both an important factor in their efficacy (Larssen, 2015). Making sure trees stay healthy during heatwaves should be an important facet of climate adaptation. This gives rise to an increased demand for freshwater, which is likely to become scarcer and more expensive (McDonald et al., 2011, in Zhao et al., 2018). For cities in a dry climate, providing cooling through greening becomes a real challenge. Higher urban temperatures also give rise to more tree pests. A study in

Raleigh, North Carolina found that a certain species of scale insects feeding on leaves and treebark were four times as numerous more numerous in the warmest areas of the city compared to the city's coolest neighbourhoods (Meineke et al, 2013, in Larssen, 2015).

Green Roofs

Green roofs have proven capable of lowering the UHI on many occasions (Fang, 2008, in Czemiel Berndtsson, 2010; Takebayashi and Moriyama, 2007, in Czemiel Berndtsson, 2010; Wong et al., 2003, in Czemiel Berndtsson, 2010; Wong et al., 2007, in Czemiel Berndtsson, 2010). A simulation for the city of Toronto by Bass et al. (2003, in Oberndorfer et al., 2007) showed an air temperature reduction of up to 2°C if 50 percent of the city roofs were to be greened. There are several different types of green roofs. Extensive green roofs have a much thinner substrate layer and offer less cooling. Intensive green roofs describe roofs that can support medium shrubs and plants, effectively being roof gardens. The thicker the substrate layer, the larger the plants that can grow on them, and the more cooling they can provide. The benefit of extensive green roofs is that they don't need much maintenance, whereas intensive roofs need weeding, fertilizing and watering (Czemiel Berndtsson, 2010).In addition to contributing to more evapotranspiration, green roofs also have a higher albedo than conventional bitumen roofing felt.

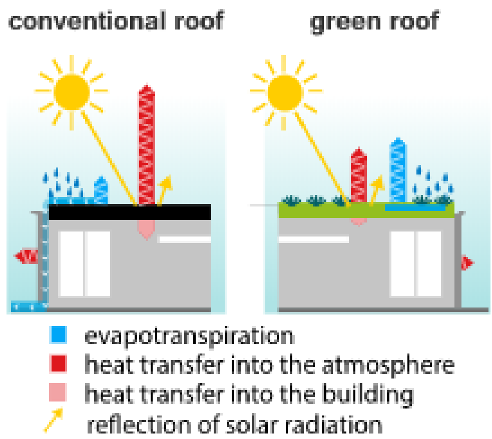


Figure 6: The workings of a green roof (Deutscher Wetterdienst, 2019)

Green walls

The greening of walls is another adaptation strategy aimed at lowering the UHI through enhanced evapotranspiration and by protecting facades and walls from solar radiation. A large benefit of vertical greening is that it doesn't take up a lot of space. Figure 7 shows the retrofit installation of a 'Standing Garden' in a neighborhood with a very small amount of public space available for greening measures.

Algae facades are emerging as a new concept in bio-architecture (Kim & Han, 2014). Algae facades screen the building from sunlight, decreasing the thermal admittance into the building. They form an extra layer around the building envelope and are composed of glaze plating encasing water in which the algae grow. The energy used for photosynthesis lowers the cooling load of buildings (Ibid.)

Figure 7: Standing Garden, Arnhem (Nexit Architecten, 2010)

Permeable Pavements

Permeable pavements are another form of cool pavements which rely on evapotranspiration in order to provide cooling. Instead of causing a quick peak runoff, porous pavements retain moisture for longer periods of time (Liu et al., 2018). There are many different types of permeable pavements with varying sizes of pores or gaps in between an impervious surface. Vegetation can grow in the larger gaps, and water can sink into the soil below. Porous pavements can store large quantities of water after a large storm depending on their thickness and also allow water to seep into the underlying soils. The overall structure still provides enough stability for heavy vehicles to move over. In a study performed by Liu et al. (2018) on the effectiveness of a special evaporation enhancing permeable pavement it was found that they are up to 9°C cooler than conventional pavements, and that the cooling effect can persist up to 7 days after precipitation. Regular pavements only continue to provide cooling for one to two days after rainfall (Li et al., 2013, in Liu et al., 2018). Permeable pavements are therefore more useful for storm water retention, and have limited effect on the UHI during long-lasting heatwaves.

Bluespace

The effect of bodies of water on the UHI is a complex matter. While ponds and streams may cause the UHI to be lower during the day, at night they emit the heat that was stored during the day. When trees hang over bodies of water they trap warm and moist air, with negative effects on thermal comfort for the direct surroundings. However, when the distance to the water is larger, complex synergies emerge. Deeper water reservoirs do not necessarily cool more, because stratification of water temperatures prevents vertical mixing (Gunawardena et al., 2017). As such, shallower waterbodies utilize more of their thermal capacity. Gunawardena et al. (2017) therefore suggest that multiple shallower waterbodies are more effective at cooling than a single (artificial) larger or deeper waterbody. Aa drawback of shallower reservoirs is that they are at a danger of drying up, after which they provide zero cooling (Ibid.). Natural features such as a river do provide significant and more stable cooling in surrounding areas when they are larger than 40 meters wide, according to Zhu et al. (2011, in Gunawardena et al., 2017).

A literature review of 27 remote-sensing studies found that waterbodies had on average a cooling potential of 2.5°C on their immediate surroundings (Volker et al., 2013, in Gunawardena et al., 2017). The average given by Gunawardena et al. doesn’t tell us a lot, because it averages the values of oceans, streams, urban rivers and streams. Upon closer inspection of the findings of Volker et al. (2013) a more detailed image emerges. A water pond with a fountain was found to be 4.7°C cooler than the surrounding park during a one day investigation period in summer. A water pond without a fountain was found to be only 1.8°C cooler. This is logical because dispersed water evaporates more easily and provides the greatest amount of cooling (Kleerekoper, 2009, in Rehan, 2016). An urban waterfront was compared with more inland sites, and an average temperature difference of 5.4°C was found here during 16 days from July to September. The tapering effect of waterbodies was also shown by comparing the temperature difference 75 meters and 780 meters from a shoreline. Closer to the shore a cooling potential of 3°C was found, while at the 780 meter mark a reduction of around 2°C was monitored.

2.2.3 Increasing advective cooling

Generating wind flows

During anticyclonic conditions when the UHI effects are at their worst, there is often no cloud cover and wind speeds are low. One of the methods to improve thermal comfort, and to decrease the intensity of the UHI is to ‘create’ wind flows. Convection of hot air can draw in air from cooler area through advection. These microscale cooling systems come into being when there is a hot-cold temperature gradient in the city. For example, a heavily built up area with a low albedo will heat up air, which starts to rise up into the air. In a nearby park, the air is denser and cooler, and is drawn to the low pressure, built up area. The rising thermals in an urban area suck in cooler air from surrounding green areas, creating a so called ‘park-breeze’ (Jansson et al., 2006, in Gunawardena et al., (2017). Doick (2014) found that bigger parks provide more advective cooling than smaller ones. These temperature gradients can also be created by increased shading, or bodies of water. Van den Dobbelsteen (2019) suggests that intentionally creating darkly colored walls or surfaces in an area can increase the advective cooling potential of an area.

Evapotranspiration was long thought to be the main contributor to the UHI. However, Zhao et al. (2014, in Gunawardena et al., 2017) state that convection plays a much larger role than evapotranspiration in cooling a city. In a study of multiple cities across the United States they found that the UHI was more significantly linked to convection efficiency than to precipitation and potential evapotranspiration. Advection and Convection are also amplified by increasing the urban roughness of an area. This can prevent saturation of the air and increase vertical mixing. For example, cooling of the UBL happens as a result of increasing the greenspace share of a city because of the increased surface roughness (Gunawardena et al., (2017). This is also why planting a variety of tree species with different heights is beneficial to the overall UHI. Creating neighbourhoods with buildings of various heights yields similar results (Grimmond, 2007). This also works synergetic with cool roofs. Constructing a tall building downwind of lowrise buildings with a cool roof helps lower temperatures in the UCL and UBL because of the increased surface roughness (Botham-Myint et al., 2015).

Urban Ventilation Corridors

In order to ensure cool advective currents can penetrate deeply into the urban fabric, urban ventilation corridors can be created. In Hong Kong the inflow of fresh air from the sea was prevented by high-rise on the shore, resulting in a higher UHI in the areas behind (Wong et al., 2010). A noteworthy example is the city of Stuttgart, which has been dubbed the coolest city in the world. It makes good use of natural wind patterns combined with a dense green network around the city (Rehan, 2016). Here, cool air moves in from the surrounding hills at night, and enters the city through green corridors flanked with trees. Street orientation therefore not only plays a role in the amount of solar radiation received, but also in the way in which advective flows can pierce into the city centre.

2.2.4 Reducing output and storage of anthropogenic heat

Reduced solar loading internally – reduce need for active cooling

The use of energy indoors for heating and cooling both contribute to the UHI. Therefore, any measure aimed at reducing energy usage indoors will help improve the urban climate. However, this is often the responsibility of homeowners, and not so much by the government. Passively cooling a house can be done by adding shades, or through the use of phase changing materials. Increasing the thermal resistance of the building by constructing a heat resistant building envelope helps insulate the house from heat penetrating into the house, and cold air escaping the house. As such, less heat builds up in the house, and no mechanical cooling is required. Mechanical cooling units such as air-conditioning blow cool air into the home, but warm air outside. Their contribution to the UHI is twofold. Not only do they generate heat, but they are often indirectly powered by fossil fuels. Other sources of anthropogenic heat include, but are not limited to, night lights (Zhou et al., 2014), motor vehicles, but also emissions (Salih, 2019; Sun et al., 2019).

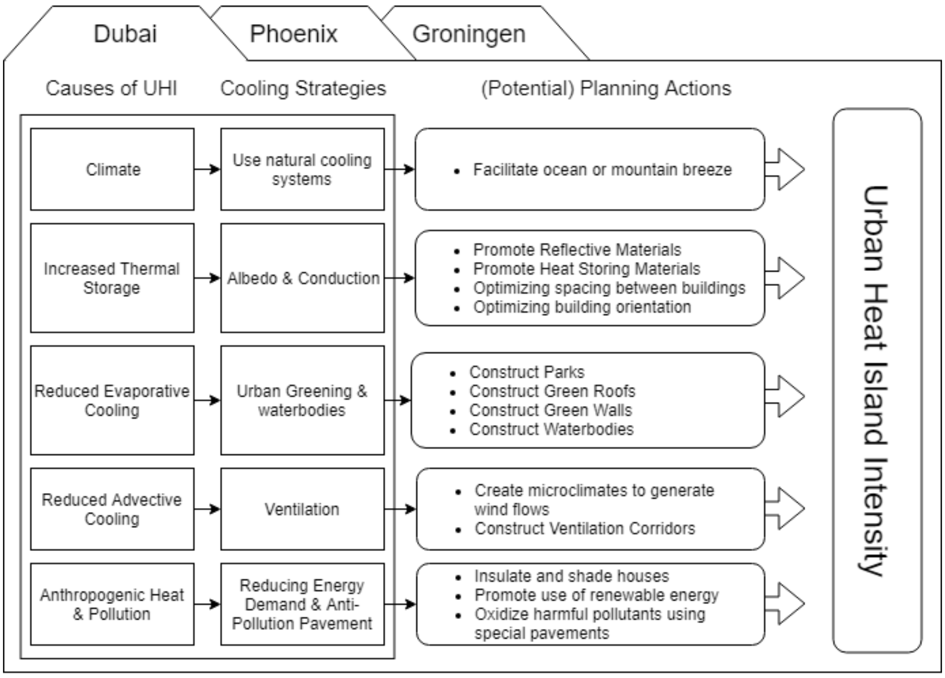
Reducing Pollution and Emissions

Changing how the energy is produced can also help contribute to a lower UHI. Particulate matter and greenhouse gases contribute to a change in the earth's energy balance. The release of carbon dioxide, methane and ozone into the lower atmosphere causes the earth to absorb more radiation. Pollution can be trapped in deep urban canyons, warming up more as a result (Johannson & Emmanuel, 2006). While the use of renewable energies is the obvious answer to prevent the release of greenhouse gases, there are also other urban design interventions that reduce the effect of the UHI. For example, there are pavement types which break down nitrogen oxides (NOx) (Wang et al., 2016; Kyriakodis & Santamouris, 2018). In a similar fashion, CO2 reduction has been attributed to a special type of concrete. Concrete which uses olivine instead of sand and gravel can absorb ten times the amount of carbon dioxide that was used to create it (Cement and Concrete Centre, 2008, in Birkeland, 2009).

2.3 Conceptual Framework

To guide the workflow of the thesis, a conceptual framework has been developed which categorizes the causes of the UHI, their respective cooling strategies, and the potential planning actions mentioned in the literature. It is based on a conceptual model made by Zhou et al. (2014) combined with the insights from Grimmond (2007) and Ramamurty and Bou-Zeid (2017). While Zhou et al. (2-14) use the built-up intensity and city size as contributors to the SUHI, this model does not. The built-up intensity and city size influence the urban heat island through increased thermal storage, and are therefore covered by the corresponding cooling strategy. Figure eight shows the conceptual model, and also hints at the three cases which are used in this thesis. The UHI is highly contextual, but the drivers are the same anywhere around the world.

Figure 8: Planning Actions to counter the urban heat island - a conceptual model



3. Methodology

3.1 Case study research

The thesis follows the principles of a case study method with extreme cases as laid out by Robert K. Yin (2008) and draws from comparative research literature from Lijphart (1975) and Rose (1991) to guide the research. A case study method was chosen because it allows the researcher to explore complex phenomena such as individuals or organizations, or a type of intervention or program (Yin, 2003, in Baxter & Jack, 2008). While case studies often investigate how these individuals or organizations operate, they can also aid in the development of theory, evaluate the efficacy of programs, or develop interventions (Baxter & Jack, 2008). In this case, interventions are being developed for the city of Groningen, based on examples from Dubai and Phoenix.

Dubai and Phoenix were selected on the basis of their a) level of development, b) climate, and c) the availability of literature. Both cities were picked because they are located in advanced nations, as suggested by Rose (1991) and Yin (2008). Because of this they are likely to have sufficient funds for a wider range of adaptation options. They are both home to research institutions such as universities and weather agencies. Both are located in a hot and arid region with high evaporation rates, having a hot desert climate. The urban heat island is well documented in both cities, and a relatively large body of literature exists on their adaptation strategies.

Yin (2008) writes that while case studies are especially well equipped to answer 'how' or 'why' questions, they can also be used to answer 'what' questions. 'What' type questions normally favor the use of a survey or archival records (Yin, 2008). This thesis does not use surveys or archival records because the temporal aspect or a trend in adaptation measures is irrelevant to the research question. Doing experiments to assess the transferability of heat-related adaptation measures was deemed too time-intensive and difficult. For this reason, literature review investigated the potential for lesson-drawing from Dubai and Phoenix.

Table 3: Research strategy per research question

Research Question	Data source
What causes *the urban heat island effect?* (Chapter 2.1)	-Literature review
Which adaptation strategies exist and which process do they target? (Chapter 2.2)	-Literature review
Which strategies do Dubai and Phoenix employ to counteract the urban heat island effect? (Chapter 4)	-Literature review -News articles, -Policy documents -Personal observation
Which strategies from Dubai and Phoenix are useful for Groningen to lower the urban heat island effect? (Chapter 5)	-Literature review -News articles, -Policy documents -Personal observation

Personal observation was done with the help aerial imagery and Google Maps 3D viewer. A drawback of using satellite imagery is that they can't measure air temperatures. For example, air temperatures may be very comfortable under a shading canopy, while the surface on top of the shading device is soaring hot. These spaces are overlooked by this method. A benefit however, is that it can be performed from anywhere on the planet. The same is true for Google Maps 3D View. It allows the researcher to look around cities without going there. A larger area can be viewed more easily in less time, and roofs and backyards can also be observed. Due to time and budget constraints, the cities could not be visited personally. The surface heat maps allow the researcher to identify cool- and hotspots in the city, and consequently look at the (lack of) adaptation measures present in the 3D viewer. This has served to back up findings from the literature and newspaper articles. To illustrate, the literature describes the use of cool roofs to lower temperatures in Phoenix. The 3D view and the surface temperature map confirm this. 3D views were not available for Dubai. This posed to be of little significance, because satellite images available on Google and online images were used instead.

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Yin (2008) states that case studies should take care of constructing validity and reliability. Special care was taken to construct validity by first building a good understanding of the concepts being studied. External validity can be achieved by properly defining the domain to which a study's findings can be generalized. In this case, the applicability of adaptation strategies from hot desert areas to a north-western European maritime climate. The scope has been narrowed as much as possible. The operations in the thesis have to be repeatable. As such, the following paragraph lays out the methodology used in the mapping of the land surface temperature (LST) and normalized difference vegetation index (NDVI) of the three cities.

The land surface temperature and vegetation coverage of Dubai and Phoenix were estimated using Landsat-8 data on the basis of an algorithm developed by Avdan and Jovanovska (2016). The Landsat-8 satellite has a thermal infrared instrument on board to capture the radiative properties of surfaces. It is superior over the MODIS satellites, because its thermal band has a much smaller spatial resolution of 100 meters, compared to 1 kilometre. The spatial resolution of a 100 meters was interpolated to a spatial resolution of 30 meters. To complement the surface UHI data, greenspace cover was calculated using the NDVI parameter. NDVI can be calculated using the spectral bands 4 and 5 of the Landsat-8 data. Emissivity values were computed using a formula by Sobrino et al. (2004). A drawback of the equation by Sobrino et al. (2004) is that the resulting land surface temperatures may be off by up to 1°C. This is not an issue, because the images only serve to locate the hotspots, and not make a definite statement about the temperatures in the city. A benefit of the NDVI-based emissivity is that the spatial resolution is higher than those that can be obtained from ASTER and MODIS satellites (Parastatidis et al., 2017). Satellite images were chosen based on the quality of the thermal imagery and cloud cover (<10%). Table 4 and 3 in the appendices give the raw data inputs that were used to calculate the LST and NDVI. The satellite data that was acquired from https://earthexplorer.usgs.gov/. Table 5 lays out the steps used in QGis raster calculator to acquire the LST and NDVI maps.

Table 4: Metadata for the spatial analysis

	Groningen	Dubai	Phoenix
DATE	26-7-2018	16-7-2018	3-8-2018
CLOUD_COVER_LAND (%)	0.77	0.00	0.00
IMAGE_QUALITY_OLI	9	9	9
IMAGE_QUALITY_TIRS	9	9	9
SUN_AZIMUTH	15.113.948.481	9.291.738.460	12.145.657.976
SUN_ELEVATION	5.362.214.072	6.692.694.577	6.383.498.830
EARTH_SUN_DISTANCE	10.156.125	10.164.338	10.146.628
RADIANCE_MULT_BAND_10	3,34E+00	3,34E+00	3,34E+00
RADIANCE_ADD_BAND_10	0.10000	0.10000	0.10000
K1_CONSTANT_BAND_10	7.748.853	7.748.853	7.748.853
K2_CONSTANT_BAND_10	13.210.789	13.210.789	13.210.789

Table 5: Calculating LST and NDVI in QGis

According to Avdan and Jovanovska (2016) land surface temperature can be calculated using the formula:
1) Ts = (BT (1 + ((λBT/ρ)ln $\varepsilon\lambda$))
Where: Ts = LST **BT** = at-sensor brightness temperature λ = 10.895 $\boldsymbol{\varepsilon\lambda}$ = emissivity $\rho = h\ c\ \sigma$ = 1.438 × 10−2 m K,= 14380
Brightness temperature and the emissivity are the only two factors that need to be calculated. Brightness temperature can be calculated by converting the digital numbers of band number 10 to top of atmosphere radiance. In order to do so, the rescaling factors found in the metadata file have to be used.
2) Lλ = M_L*Qcal+A_L = M_L*Q_{cal}+A_L
where: L_λ = TOA spectral radiance M_L =Band-specific multiplicative rescaling factor from the metadata A_L=Band-specific additive rescaling factor from the metadata Q_{cal} = Quantized and calibrated standard product pixel values
Spectral radiance was then converted to top of atmosphere brightness temperature using the thermal constants found in the metadata file.
3) BT = (K2/(ln(K1/L_λ)+1))−273.15
Where: BT = Brightness temperature K1 = K1 constant band 10 from the metadata K2 = K2 constant band 10 from the metadata $L_{\lambda\,=}$ TOA spectral radiance -273.15 = Temperature conversion from kelvin to ℃
In order to calculate the emissivity which is needed for calculating the LST, the NDVI was first calculated using the near infrared band 5and the red band 4.
4) NDVI = ((band 5) − (band 4))/((band 5) + R (band 4))

The minimum and maximum NDVI on the map can then be used to calculate the proportion of vegetation using:
5) Pv = ((NDVI−NDVImin)/(NDVImax−NDVImin))2
The vegetation fraction is then used to calculate the emissivity, which allows for the calculation of the LST. Land surface emissivity can be obtained using Sobrino et al. (2004) their formula:
6) ε=0.004Pv+0.986

4. Adaptation to the urban heat island in Dubai and Phoenix

Each case follows the following structure: 1) the adaptation strategies in […] 2) The Urban Heat Island, 3) Climatic drivers of the UHI, 4) Decreasing the thermal load, 5) Increasing evaporative potential, 6) Increasing advective cooling potential, 7) Reducing output and storage of anthropogenic heat. The sources for the adaptation strategies can be found in the appendix chapter.

4.1 Dubai

Dubai is the largest city in the United Arab Emirates and totals a population of around 1.1 million. It is situated right under the tropic of cancer and is one of the driest regions of the world. Summer temperatures are extremely high, averaging above 40°C in the months of July and August. Dubai stretches along the Persian Gulf and is subjected to high humidity rates in summer, which often reach up to eighty or ninety percent. The extreme temperatures and humidity have made living conditions in this area very harsh. They have given rise to a range of ancient, as well as modern innovations that allow Emirates to live comfortably.

Dubai is famous for its modern architecture, and was the first city in the Middle East to receive a platinum LEED (Leadership in Energy and Environmental Design) rating in April 2019 (Gulf News, 2019). LEED ratings are an internationally recognized sustainability standard given out to buildings, communities and cities. Achieving this award has been the result of Dubai's Green Building Regulations, which focus on energy savings, and re-use of waste water and heat. Dubai's older architecture incorporates passive cooling methods, while modern architecture often relies on air-conditioning. Indraganti and Boussaa (2017) report that around 80% of all the energy in Dubai is used for air conditioning in buildings. Efforts aimed at reducing the carbon footprint and energy use are resulting in a re-appreciation of traditional architectural elements, because of their passive cooling capabilities. This reduces the need for air-conditioning.

The Municipality of Dubai is comprised of many different neighbourhoods, and is practically a city of cities. The areas nearest to the coast are mostly comprised of low and medium-rise buildings, while skyscrapers dominate the landscape further inland (Figure 9). The city is expanding faster than its population is growing, adding more low density suburbs. The new neighbourhoods often feature pools and ponds, as well as vegetation. As a result, they are often cooler than the surrounding desert (Frey et al., 2007).

Figure 9: Skyline of Dubai (hamza82, 2012)

4.1.1 Adaptation strategies Dubai

Dubai has grown enormously over the past few decades and has evolved into a true metropolis. It employs several strategies to minimize the impacts of the urban heat island, which are listed in table 3. They are discussed in depth in -depth in the following paragraphs.

Table 6: Cooling strategies in Dubai

Cooling Strategies - Dubai	Climatological cooling	Decreasing thermal load	Evaporative cooling	Advective cooling	Reducing waste heat	Nighttime UHI	Thermal comfort	Precipitation
Sea breeze	•							
Densification		•		•		▲		
Shaded walkways		•						
Courtyards		•	!					
Trees and parks		•	•	•		▲		
Wind towers			!	•				
District cooling					•			
C02 neutral vehicles					•			

! – Potential cooling benefits depending on type (e.g.: a courtyard outfitted with a fountain or a wind tower with wetted pads may benefit from evaporative cooling)

▲/▼ – Potential increase/decrease in nighttime UHI, thermal comfort or precipitation

4.1.2 The urban heat island of Dubai

Dubai has a daytime surface urban cool island (SUCI) (Frey et al., 2007). Temperatures are about 5°C lower in the city than in the surrounding countryside, which is mainly desert. Even industrial areas without vegetation have lower surface temperatures than the sand in the desert. Parks and golf courses form the cool spots of the city, and bodies of water have the lowest surface temperature (Frey et al., 2005). The continuing growth and urbanization of the city has increased the city's heat sink effect, which prevents it from cooling down at night. Zacarias (2011, in Rajabi & Abu-Hijleh, 2011) identified three hotspots within the city. Two of them are densely built up areas in an older part of the city, and a third is the industrial area of Al Qouz. From Frey et al. (2007) and the maps made in GIS it becomes evident that the urbanized areas are still cooler than the desert. Figure 10 gives an overview of the study area. This specific area was chosen because it shows the old town, industrial areas and the desert, as well as the central business district with its high-rise. Figure 11 shows the land surface temperature map for the same area, while figure 12 shows the normalized difference vegetation index.

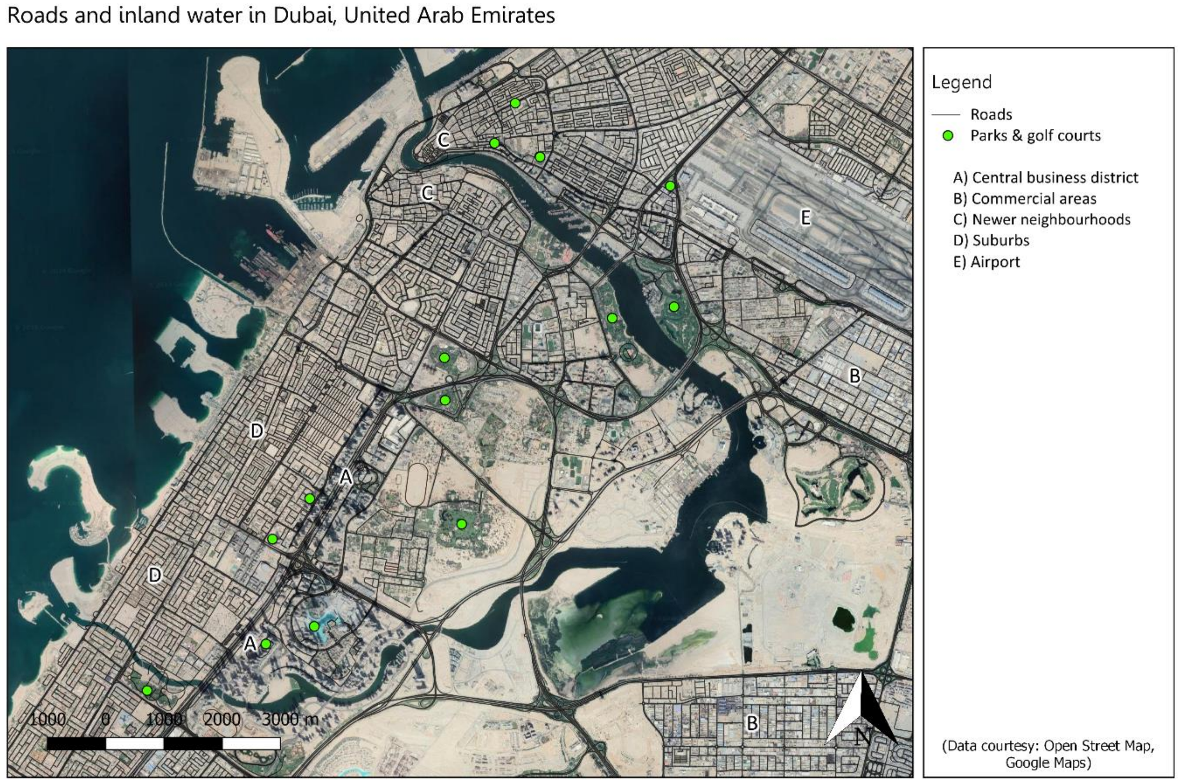

Figure 10: Overview of the study area in Dubai

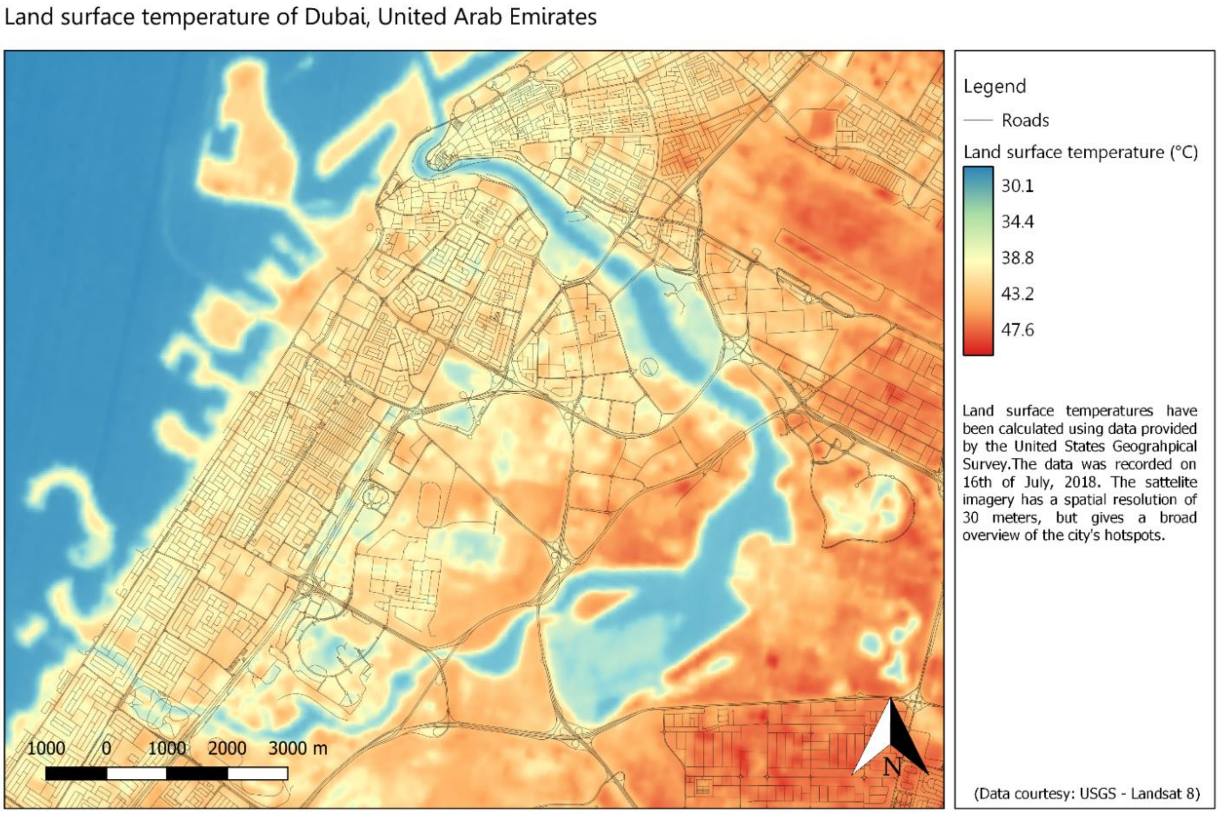

Figure 11: Land surface temperature map of Dubai

Normalized difference vegetation index (NDVI) of Dubai, United Arab Emirates

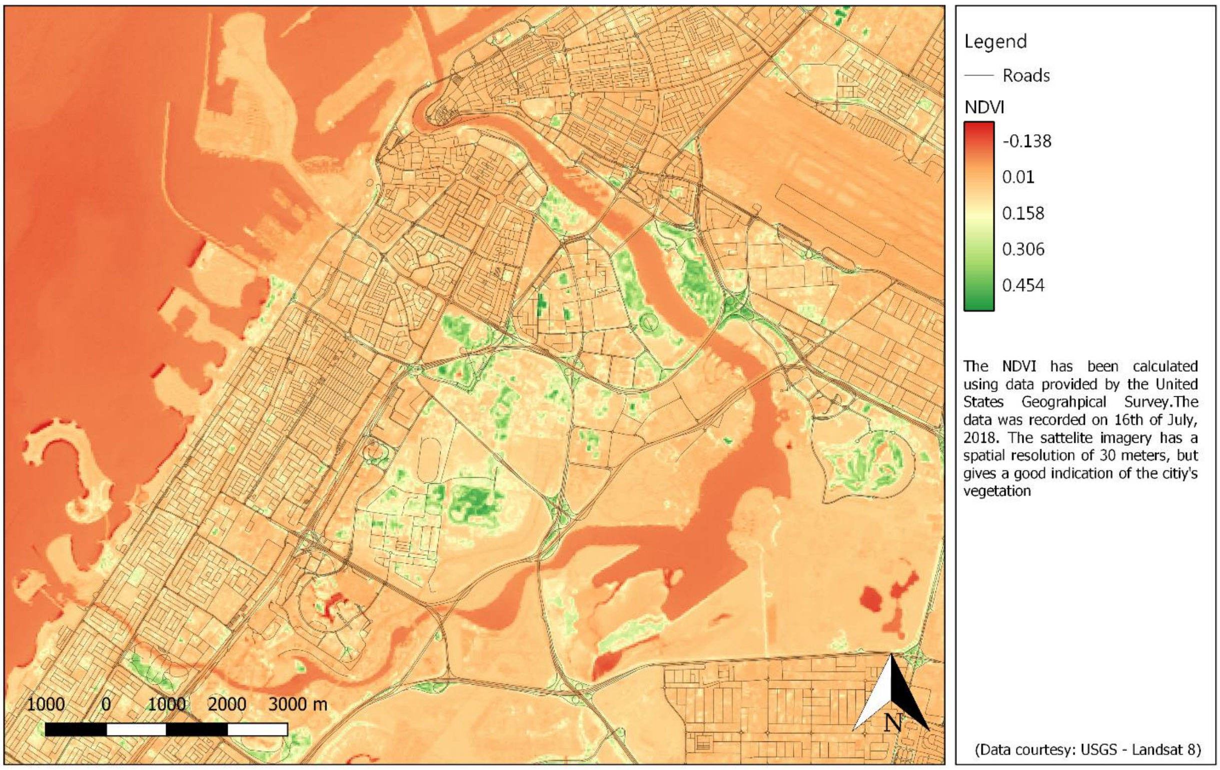

Figure 12: Normalized difference vegetation in dex of Dubai

4.1.3 Climatic drivers of the UHI now and in 2050

The climate of Dubai is moderated by its proximity to the Persian Gulf. The pressure gradient between the air above the city and the water gives rise to consistent wind flows from the North West (Figure 13). The wind is on average cooler than the temperatures in the city, because it is cooled by the ocean (Al-Sallal & Al-Rais, 2011). The minimum wind speed in winter is 3 m/s in winter, and 3.75 m/s in summer (Ibid.). The advective cooling can be enhanced by exploiting these winds (Chapter 4.1.5). Winds which hit the city from the south are warmer and often produce sandstorms (Ibid.).

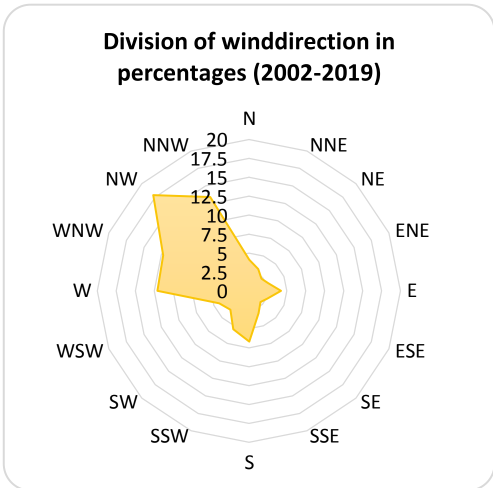

Figure 13: Division of winddirection percentages Dubai (Windfinder, 2019

4.1.4 Decreasing the thermal load

Reflective materials

The city of Dubai receives a lot of solar radiation. Dubai employs several strategies of keeping temperatures low in the city. Increasing albedo, or using reflective materials, has been introduced in the literature review as one of the means to do so. The Government of Dubai (2009) mandates the use of reflective roofs on its public buildings as part of an effort to limit the urban heat island, as stated in the Green Building Guidelines that were released by the Government of Dubai and the

Ministry of Public Works. Many buildings in Dubai are already light of colour (own observation using Google maps, 2019), but still have a lower albedo than the desert. Conversely, the desert is hotter during the day. Shadows contribute to a lower albedo, and also to lower temperatures.

Optimizing the spacing and orientation of buildings

The lower temperatures in the city are due to the shading that the buildings provide. Streets with high H/W ratios are one of the reasons for Dubai's urban cool island. Especially old Dubai features many narrow alleys, courtyards and covered markets or souks. Traditional, deep urban canyons with an H/W ratio of 2.2 can be up to 10°C cooler than modern canyons with a ratio of 0.42 (Bakarman & Chang, 2015). Courtyards with a high H/W ratio also benefit from added cooling due to shading. The courtyard architecture is characteristic of many Middle Eastern cities. It makes use of several of the cooling strategies described in chapter 2.3. The evaporative potential can be increased when the courtyard is vegetated, or when a basin or fountain is present (Abdulkareem, 2016). It is not uncommon to spray the surface floor of the courtyard with water in the morning, so it stays cool longer. Advective cooling occurs due to the rising thermals in the centre of the courtyard, which draw out cool air from the adjoined rooms (Ibid.). Traditional covered markets and shaded pedestrian walkways are also two ways in which the surface urban heat island is kept at bay (Haggag, 2010).

Buildings are also encouraged to use slope roofs, or cascaded roofs (Government of Dubai, 2009). These types of roofs slant downwards towards the north in order to receive the least amount of radiation.

4.1.5 Increasing evaporative potential

Trees and parks

Frey et al. (2007) conducted an analysis of the urban heat island of Dubai using satellite data and thermal imagery by the municipality of Dubai. The analysis of surface temperature showed that areas with a higher NDVI typically also have lower surface temperatures. However, the correlation between them is not very strong (ibid.). Extra parameters such as distance to water and land use were needed to create a stronger correlation. Arguably, the distance to water is a proxy for wind speeds, and refers to the climatic cooling that is offered by the ocean. Wind speeds are higher near the coast where they are unobstructed by buildings. Additional research on the interrelation between vegetation and distance to water may be needed for Dubai. However, figures 10 and 11 do show that vegetated areas are generally cooler. Rajabi and Abu-Hijleh (2011) found that the type of vegetation in Dubai is an important factor in the degree to which they can provide cooling. Grass provides the lowest cooling, because of its low complexity and limited shading. Shade trees have been found to be much more effective (Rajabi & Abu-Hijleh, 2011).

Green roofs

The Green Building Guidelines promote the use of green roofs as an optional measure for new government buildings (Government of Dubai, 2009). However, green roofs in Dubai were found to have a very limited cooling effect on surface temperatures (Rajabi & Abu-Hijleh, 2011; Taleb & Abu-Hijleh, 2013). Rajibi and Abu-Hijleh (2011) write that this is due to the fact the cooling effect of green roofs does not extend towards street level, and is sharply reduced by distance. Even though the effects on the urban heat island are small, green roofs can still be used to build more energy efficient buildings. According to Haggag (2010) green roofs and green walls are rarely used in Dubai. Personal observation confirms this, though because there is no 3D viewer available for Dubai, it is hard to make out whether greenspace is at roof level or not.

4.1.6 Increasing advective cooling potential

Generating wind flows

Dubai is favoured by strong winds coming from the Persian Gulf in summer, and uses these winds for cooling. Al-Sallal and Al-Rais (2011) found that the narrow streets of Dubai in the old district accelerate the wind passing through it, and deliver a higher passive cooling performance than wide streets. A drawback is that eddies can form when there are a lot of corners. When wind speeds are relatively high at 5 m/s, wind penetrates deeper into the city. Here the high H/W ratio's (2 to 0.67) provide an additional cooling benefit by accommodating light or gentle breezes. While the impact on the UHI is not mentioned in the study of Al Sallal and Al-Rais (2011), higher wind speeds also accelerate the convective heat loss of urban materials. Advective flows are especially benefit for thermal comfort. The light and gentle wind breezes can result in temperatures which feel 5°C to 8.5°C lower than the local air temperature (Ibid.).

Wind Corridors

While narrow alleys speed up the wind, the configuration determines how well it penetrates into the city. A study performed for the traditional neighbourhood of Bastakiya by Taleb and Abu-Hijleh (2013) showed that it was more effective at lowering temperatures than a grid-neighbourhood. For cooling the neighbourhood it was concluded that streets should be aligned parallel to the prevailing wind. Due to Bastakiya's organic layout, wind provided the most effective cooling. The grid-neighbourhood achieved higher wind speeds, but not lower average temperatures. This is due to the cross-streets where wind speeds are very low. Cooling is limited to the streets which are parallel to the wind direction.

Wind towers

Wind speeds are generally higher at higher altitudes. A middle-eastern innovation which exploits these winds is the wind tower, or '*Badgir*' (Figure 15). Wind towers redirect prevailing winds into courtyards or homes due to a pressure gradient which exists between the top of the tower and the base (Bahadori, 1985, in Santamouris, 2012). The advective cooling that is provided by the resulting breeze can be enhanced by adding an evaporative component. A shallow pond of water can be added at the base, or damp cloth can be hung at the top of the tower.

Figure 14: A traditional wind tower in Dubai (McKay Savage, 2010)

Santamouris (2012) identifies a few drawbacks to these towers. First, they are inefficient at low wind speeds. Secondly, the cooling potential is limited because the contact between the air and the moist surfaces are lacking. Thirdly, Santamouris (2012) states that the aerodynamic design of the tower is not optimized. According to Osman and Sevinc the potential of wind towers is limited in dense urban areas where the wind flows are negatively impacted by buildings. Wind catchers perform well when wind speeds are above 3 m/s (Bahadori, 1985, in Soutullo, et al., 2012). When wind speeds drop below 3 m/s, the wind catcher heats up and drives heat upward and out of the building (Ibid.). New wind tower designs incorporate fans and solar panels to overcome these problems (Soutullo, Sanjuan, & Heras, 2012).

4.1.7 Reducing output and storage of anthropogenic heat

Some of the historical buildings in Dubai feature shutters and overhangs which provide shade to windows, while allowing for air to flow through the building (Sayigh, 2013). Shutters and overhangs can achieve a reduction in cooling costs by up to 7% and 10% respectively (Ibid.). Sayigh (2013) notes that newer buildings in Dubai are very rarely equipped with shutters. This same observation was made when walking around in the centre of Dubai in Google Maps Streetview. Figure 16 shows a generic façade near Dubai's old town, illustrative of contemporary construction practice.

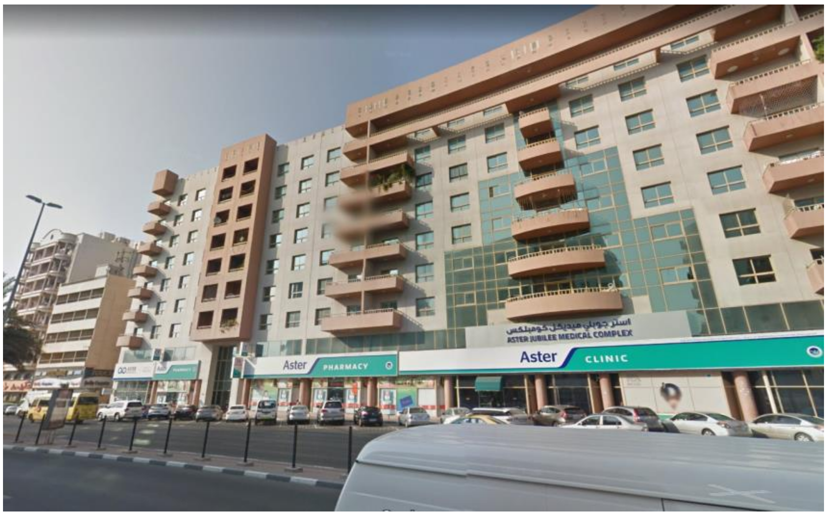

Figure 15: The Aster Jubilee Medical Complex as seen in Google Street View (Google Maps, 2019):

The car has long been the main mode of transport in Dubai. The municipality focused on building roads and accessibility by car. However, policy is shifting to other modes of transport. A light rail now connects the southern areas of Dubai to its international airfield in the north. Dubai has a driverless metro system, which saw ridership increase from 60,000 daily commuters in 2009 to 500,000 in 2014 (Gulf news, 2014). Dubai furthermore aims to ensure that twenty percent of all trips in the city are made with public transport by 2020, and thirty percent by 2030. Currently fourteen percent of all trips are made by taxi, bus or metro (ibid.).

Dubai is home to one of the largest district cooling facilities in the world. District cooling provides cool air to a large amount of shopping malls, hotels, and residences. District cooling can achieve a 50% reduction in energy use compared to traditional air-conditioning units. It currently services over a 100,000 customers (EMPOWER NEWS, 2019). Grimmond (2007) states that district cooling is one of the ways to reduce the release of anthropogenic heat in city centres. The direct effect of district cooling has not been researched for the city of Dubai, but it is likely that it makes a contribution to lower air temperatures in the area.

4.2 Phoenix

Figure 16: Central business district of Phoenix (Melikamp, 2011)

Phoenix is one of the hottest cities on the planet, and its climate compares to the hot desert climate of the Sahara. Despite the heat, the city still has a population of around 1.6 million people (U. S. Census Bureau, 2019). It has one of the lowest population densities, with 1280 people per square kilometre. Like many other American cities it has a central business district (CBD) with high density development and high-rise, and is surrounded by low-density low-rise (Figure 17).

Climate change and population growth are putting increased stress on Phoenix' long-term sustainability; it is threatened by water shortages, a reduction of biodiversity, poor air quality and the urban heat island (Chow et al., 2012).

4.2.1 Adaptation strategies Phoenix

Phoenix has been at the forefront of urban heat island research. It has developed two broad plans aimed at reducing urban temperatures. The first is the Cool Roof Initiative, which aims to lower temperatures by increasing the albedo of the city's roof surfaces.. The Master Shade and Tree Plan is a second policy which aims to plant more shade trees, and replace asphalt with vegetated soil. Table 7 gives an overview of the adaptation strategies used in Phoenix to counteract the UHI. The following paragraphs discuss the adaptation strategies in-depth.

Table 7: Cooling strategies in Phoenix

Cooling Strategies - Phoenix	Climatological cooling	Decreasing thermal load	Evaporative cooling	Advective cooling	Reducing waste heat	Nighttime UHI	Thermal comfort	Precipitation
Reflective pavement		•					▼	▼
Reflective roofs		•						▼
Photovoltaic shading devices		•						
Building orientation		•		!				
Shade trees		•	•			▲		
Trees and parks		•	•	•		▲		
Permeable pavements		!	•					
Misting installations			•				▲	
C02 neutral vehicles					•			

! – Potential cooling benefits depending on type (e.g.: building orientation can improve wind flows, and permeable pavements can be reflective)

▲/▼ – Potential increase/decrease in nighttime UHI, thermal comfort or precipitation

4.2.2 The urban heat island of Phoenix

The urban heat island of Phoenix is well documented. It was first surveyed in 1921 by Gordon, who mapped isotherms for the surroundings of Phoenix. Since then, more than 55 UHI studies have been conducted in the area (Chow et al., 2012). The strong difference between the nocturnal and daily UHI is most evident in the CBD. While the CBD is coolest during the day, it is the hottest in the early evening and during the night. Temperatures can be as much as 11℃ warmer than the countryside (di Sabatino et al., 2009). There is a chance that minimum air temperatures in the city centre will never drop below 38°C (Ibid.). Figure 18 gives an overview of the study area within Phoenix and marks the parks of the city. These same parks can be observed as cool spots in figure 20, and as areas with a high NDVI in figure 21. Figure 19 shows that the airport is one of the few open areas with relatively low NDVI values and high temperatures.

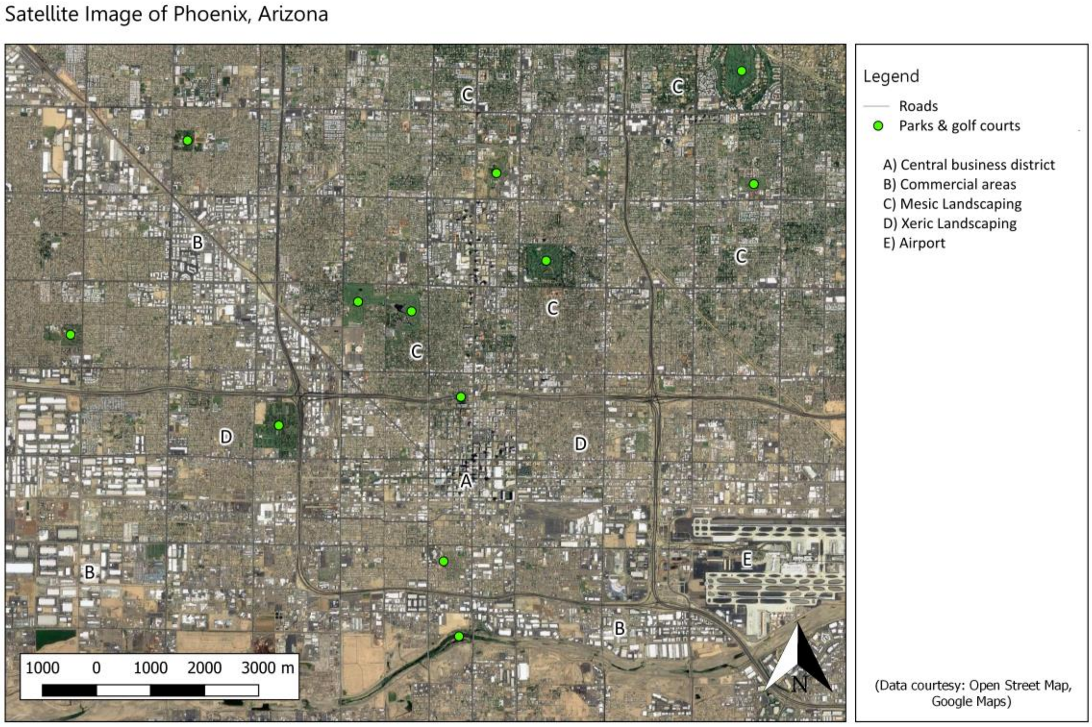

Figure 17: Overview map of Phoenix

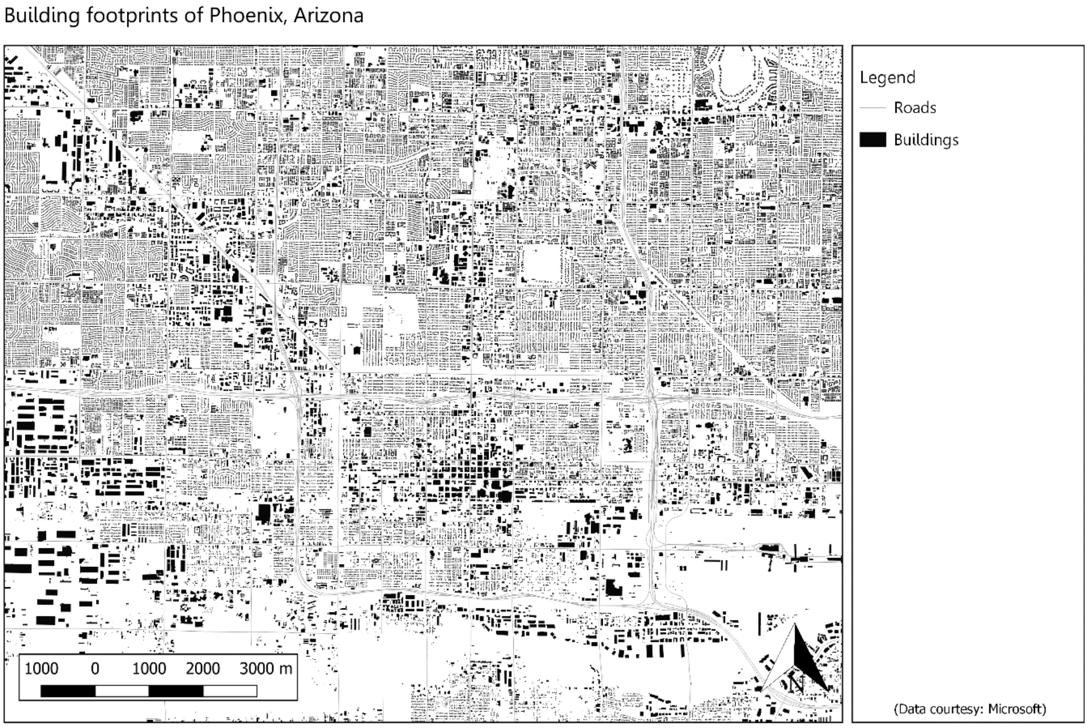

Figure 18: Building footprints in Phoenix

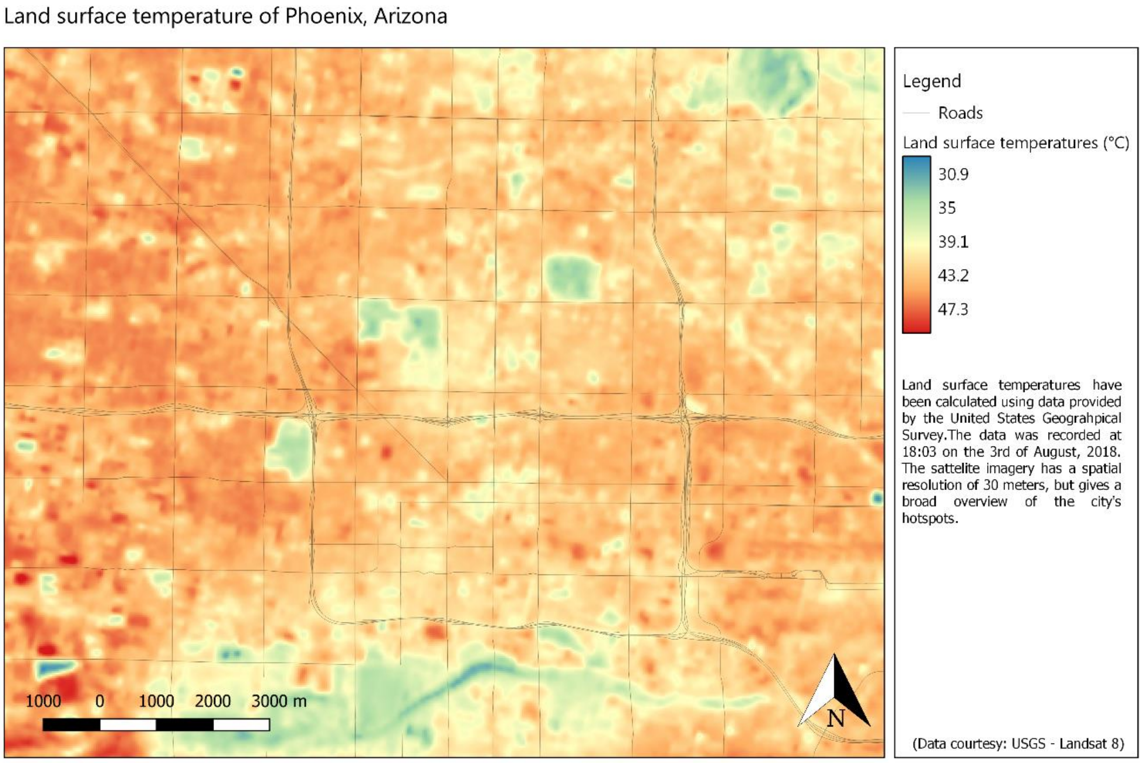

Figure 19: Land surface temperature map of Phoenix

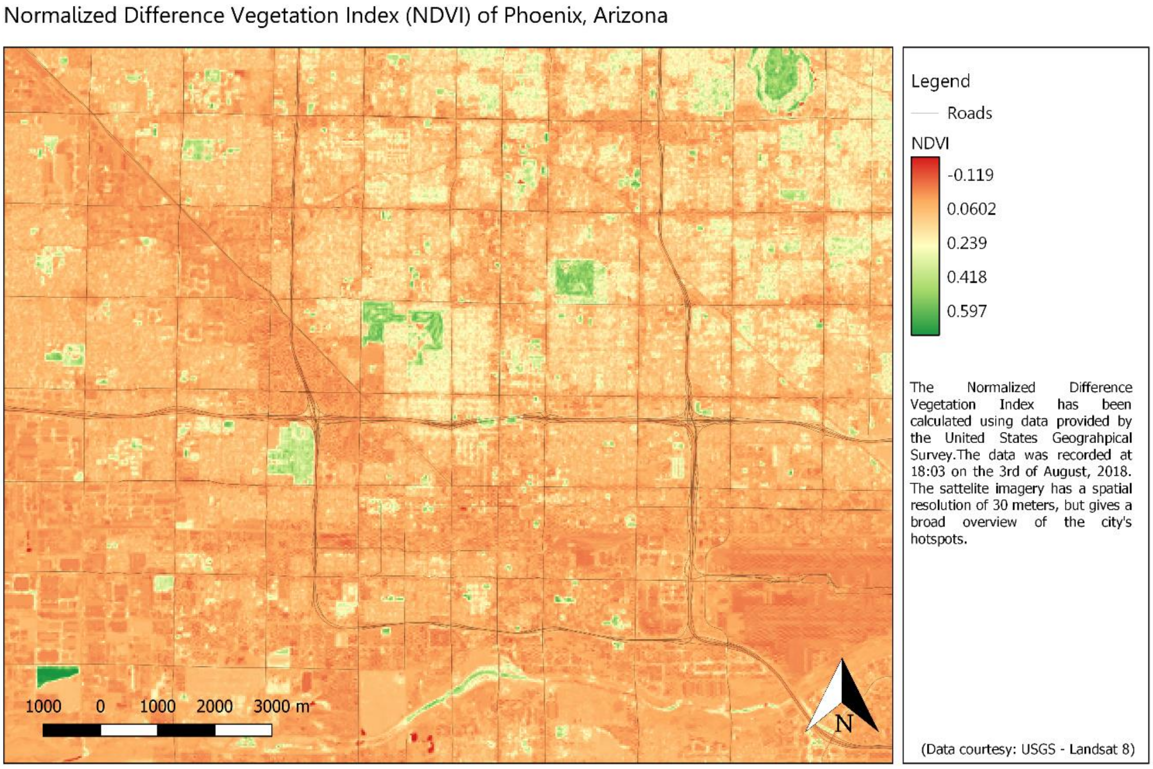

Figure 20: Normalized difference vegetation index map of Phoenix

4.2.3 The climatic drivers of the UHI

The UHI in Phoenix is caused by high pressure conditions which dominate the American South-West for 70 percent of the year (Wang & Angell, 1999, in Brazel et al., 2005). Wind speeds are generally low. Wind flows around Phoenix arise mostly due to the urban heat island effect, which produces gentle breezes of around 1 to 3 m/s (Ibid.). Natural wind flows are found in the evening near the hills in the north east of the city, where light mountain breezes descend into the valley. They bring some cooling to the suburbs on the edge of town, but do not penetrate deep into the city (Brazel et al., 2005). The potential for cooling during the day is very limited, and is not mentioned in any of the researched articles.

4.2.4 Decreasing the thermal load

One of the focal points of Phoenix adaptation program is decreasing the thermal load. It does so through the Phoenix's Cool Roof initiative which was launched in 2013. The initiative aims to decrease the net radiation that is absorbed by the city. A study performed in Phoenix by Emmanuel and Fernando (2007) already found that the high albedo roofs achieved limited cooling (+- 1°C) during the day, and caused slightly higher temperatures at night. Similar findings are presented in an assessment of the adaptation strategies used in Phoenix in 2014. The Arizona state university found that cool roofs in phoenix achieved a temperature reduction of 0.22 to 0.28° Celsius in neighbourhood air temperatures (City of Phoenix, 2014). Cool roofs in Phoenix do not meet up to the 3°C reduction which was found in the literature by Botham-Myint et al. (2015).

Furthermore, the use of reflective roofs can decrease the total amount of precipitation. Georgescu et al. (2012, in Botham-Myint et al. 2015) found an annual reduction in precipitation of 4% within the greater metropolitan area of Phoenix due to reflective surfaces. In addition, reflective roofs may reflect solar energy towards other buildings, which may warm up more as a consequence.

Shading

The CBD of Phoenix is one of the coolest areas in the city during much of the day (Figure 20). It is only in the afternoon when temperatures start to get comparatively higher. This is due to the high H/W ratios in the city centre, where shade is provided by high-rise. Temperatures in the CBD are on par with the temperatures in the parks as can be observed from the land surface temperature map shown above.

Figure 21: Shade and shading canopies in the CBD of Phoenix (Google maps, 2019)

Phoenix uses shade canopies to lower urban temperatures. They are especially common in parking lots, but are also used at the Central Station. Both can be seen in figure 22, with the central station marked on the left**.** Figure 22 also shows the shading caused by the high-rise in the central business district.

Some of the shade canopies are equipped with solar panels. Golden et al. (2007) advocate the use of photovoltaic canopies over parking lots instead of using trees for shade. Their study in Phoenix found that covering parking lots with an artificial roof nets higher reductions in surface temperatures. They argue that trees are insufficiently able to cope with the extra radiation they receive, and the more limited access to water. The photovoltaic canopy achieved a surface temperature reduction of 13.2°C, where urban forestry achieved a reduction of 6.2°C.

4.2.5 Increasing the evaporative potential

Trees and parks

A second official strategy of the city of Phoenix is the Master Tree and Shade Plan, which actively promotes the use of trees along traffic axes of the city, as well as in residential neighbourhoods. It aims to reach a 25% canopy cover by 2030 (City of Phoenix, 2010). A modelled increase in tree canopy cover from 10 to 20 percent resulted in a reduction in air temperatures by up to 2°C. However, more trees put a strain on Phoenix' water supply. 60 percent of Phoenix water is used for outdoor irrigation. This is why city strives to plant a maintainable, drought-resistant urban forest. It also encourages homeowners to convert their lush, 'mesic' gardens to low-water demand 'xeric' vegetation.

The mesic gardens are non-native landscaping features which have significantly lower surface temperatures than xeric gardens, but are likely to be less sustainable (Chow & Brazel, 2012). The city of phoenix encourages homeowners to switch to xeric gardens with a onetime subsidy of US$ 500,- (Ruddell & Dixon, 2014). Chow and Brazel (2012) found that the drought resistant shade trees in a xeric garden can provide a cooling of around 2.5°C at the micro-scale, and a reduction of 1.1°C at the local, neighbourhood scale. However, converting all gardens would result in higher urban temperatures (Ibid.). An ENVI-MET simulation for a xeric neighborhood with no tree cover and regular roofs predicts that air temperatures may increase up to 43.9°C in a high emission-scenario Middel et al., 2015). Under current climate conditions and with a 25% tree canopy cover and cool roofs, air temperatures can reach up to 37.4°C, which is 2°C cooler than the current situation (Ibid.). Many of the coolspots seen in the land surface temperature map (Figure 20) are parks, as can be deduced from the NDVI map (Figure 21), demonstrating their cooling potential.

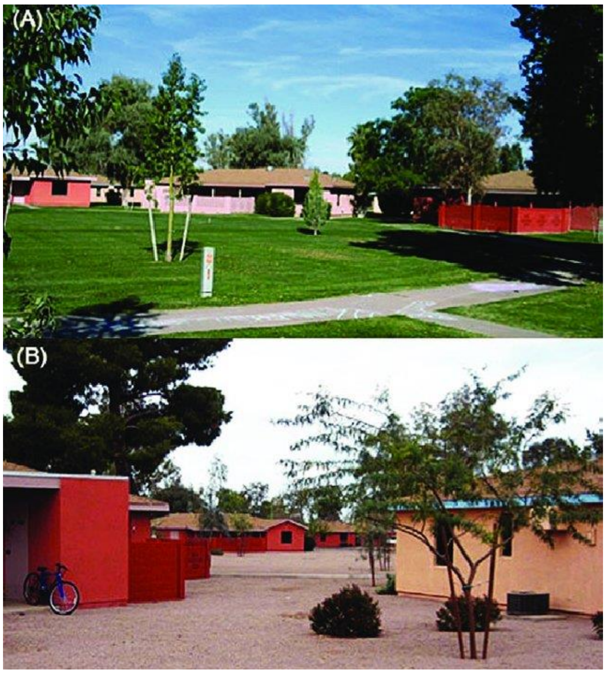

Figure 22: A) Mesic garden compared to a B) xeric garden (CAP LTER, 2019)

Waterbodies

There are no large waterbodies that cool Phoenix. However, as part of the Downtown Phoenix Urban Form Project, evaporative moisture misters have been proposed as a means to ameliorate the downtown UHI (Chow et al., 2012). Vice News (2018) reports the use of evaporative misters on a prototype bus stop, which is monitored by the Arizona State University. No results of this study were found online yet. There is no further mention of misting fans in phoenix the literature and misting fans are too small to show up in Google Maps 3D viewer. As a result, not much can be said about the how widespread the use of misting fans is in Phoenix.

4.2.6 Increasing advective cooling

A chapter in The Downtown Phoenix Plan (2008) written by the Arizona State University and an architecture firm suggest an ideal building form with different building heights which could improve the circulation of air in the city centre (Figure 21). It is unclear whether this vision document actually guides future developments. Academic literature and actual policy documents make no further mention of improving the advective cooling potential in the city elsewhere. Phoenix does not actively promote the use of wind corridors, nor is there any mention of them in the researched literature. A

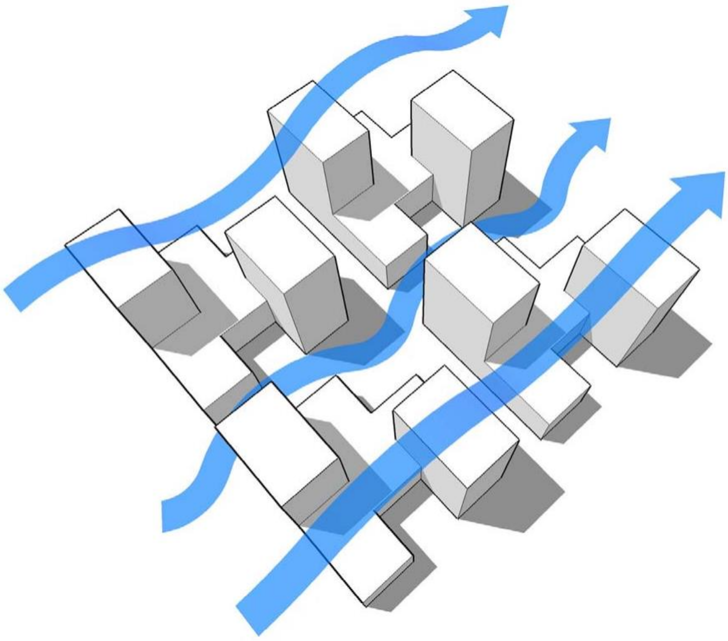

Figure 23: Optimum canopy airflow (City of Phoenix, 2008, p. 4-10)

4.3.6 Reducing output and storage of anthropogenic heat

Like Dubai, Phoenix makes use of district cooling. Phoenix has three cooling plants operated by the NRG energy centre. They cool around 40 buildings in downtown phoenix with a total surface area of more than 1.1 square kilometres (FOX, 2017). Over the last few decades, Phoenix has been transitioning towards more sustainable modes of transport (City of Phoenix, 2009; Homrighausen & Tan, 2016). Bicycle and walking infrastructure has been improved and light rail services and bus rapid transit facilities were constructed (Homrighausen & Tan, 2016, STV, 2013). Improving walkability by lowering the UHI and improving thermal comfort was also one of the key suggestions of the Phoenix Downtown Urban Form Project (City of Phoenix, 2008)

5. Adaptation to the urban heat island in Groningen

This chapter first introduces Groningen in a similar fashion to Dubai and Phoenix in chapter 5.1. Chapter 5.2 is aimed at drawing lessons from the adaptation strategies of Dubai and Phoenix. It does so comparing the three cases, and showcasing the different approaches of Dubai and Phoenix and applying them to Groningen. Chapter 5.3 features a discussion, which assesses the potential of the adaptation strategies in a north-western European setting.

5.1 Groningen

Groningen is a university town in the north of the Netherlands and has a population of around 200,000 people (CBS, 2019). It has a temperate maritime climate with mild winters and warm summers and can be classified as having an ocean climate (Cfb). It is a densely populated city, with 2,137 people per square kilometre. Most of its neighbourhoods are comprised of low-rise buildings, with the exception of the city centre and the areas around the highways, which have a few taller churches and high-rise towers respectively. Figure 22 gives an impression of Groningen's low-rise historical city centre.

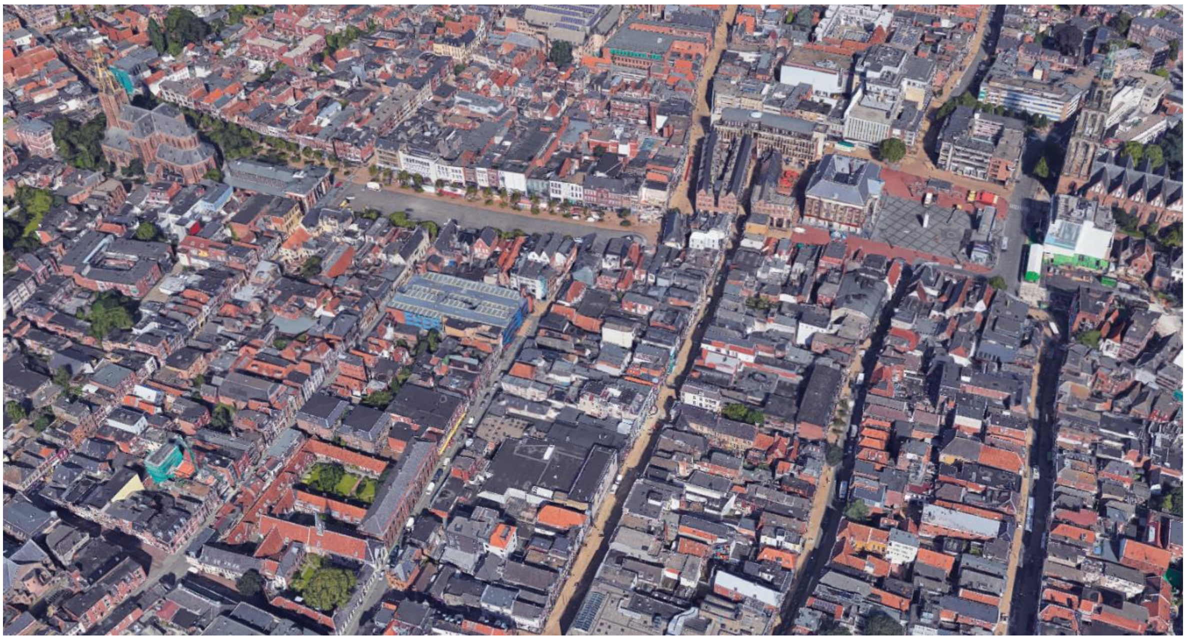

Figure 24: City centre of Groningen (Google maps, 2019)

Groningen is home to the municipal council of the municipality of Groningen, which also encompasses the neighbouring towns of Haren and Ten Boer. It is responsible for most of the urban planning within the city, and has a special department for it called the 'Dienst Ruimtelijke Ordening en Economische Zaken' (Office of Economics and Spatial Development).

Its dedication to solving the climate crisis by increasing its mitigation and adaptation efforts shows in several ways. For example, Groningen's mayor signed the Global Covenant of Mayors for Climate Change and Energy on the 31st of May in 2017 (Covenant of Mayors, 2019). In doing so, the municipality commits itself to decreasing its carbon dioxide output, and to becoming more resilient, and adapting itself to the effects of climate change. It is also a key player in a climate-initiative of the northern Netherlands, in which a range of municipalities, provinces and business work together to share knowledge of sustainable development and planning practices (Climate Initiative Northern Netherlands, 2019). The Dutch state also mandates making risk and impact assessments of climate related weather disasters such as droughts and floods. As such, adaptation in Groningen is already quite advanced. However, they also admit that not much attention has been given to implementing climate related adaptation strategies in public areas (Gemeente Groningen, 2016, p. 10). A climate adaptation plan is to be completed in 2020 (Gemeente Groningen, 2018), which prepares buildings and neighbourhoods to counter the negative effects of climate stress. As an example they note that nursing homes have to be heat resistant.

5.1.1 Adaptation strategies Groningen

Groningen is well on its way to becoming a climate proof city, and has several policies in place to mitigate the urban heat island. In its adaptation effort it is largely focusing on greening measures. Table 8 gives an overview of the adaptation strategies used in Groningen to lower the UHI.

Table 8: Cooling strategies in Groningen

Cooling Strategies - Groningen	Climatological cooling	Decreasing thermal load	Evaporative cooling	Advective cooling	Reducing waste heat		Nighttime UHI	Thermal comfort	Precipitation
Reflective pavement		•						▼	▼
Trees and parks		•	•	•			▲		
Green roofs		!	•	!	•				
Vertical greenery		•	•		•				
Canals			•				▲		
Permeable pavements		!	•						
Fountain*			•						
C02 neutral vehicles					•				

! – Potential cooling benefits depending on type (e.g.: building orientation can improve wind flows, and permeable pavements can be reflective)

▲/▼ – Potential increase/decrease in nighttime UHI, thermal comfort or precipitation

5.1.2 The urban heat island of Groningen

Over the past few years, the municipality has expanded its knowledge about its UHI. In 2012, Klok et al. showed that the surface urban heat island (SUHI) in the Netherlands can be as high as 9°C. They investigated the intensity of the UHI during the heat wave of 2006. For Groningen however, they found that the average SUHI during the day was 2°C, while at night it was found to be 3.2°C. Comparing this with the national average, Groningen was 0.9°C cooler during the day, but 0.8 degrees warmer during the night. Klok et al. attribute the differences between nocturnal and diurnal UHI intensities to soil type. They state that cities built on clay have higher nocturnal heat islands, whereas cities built on sand have higher diurnal heat islands. However, this data was derived off satellite data from two NOAA-AVHRR[1] satellites which have a fairly limited spatial resolution of one kilometer. Using the LANDSAT-8 sattelite data could have provided more accurate temperature readings for the city, and the UHI could potentially be more pronounced.

In 2018, a climate stress test was performed by Sweco which used LANDSAT-8 satellite data, and combined it with shading patterns during the day. As a result, a more fine grained heat stress map was produced. The map highlights that especially the densely built up city centre, the area due west of it, and the area around the train station are subjected to heat stress (Sweco, 2018). A map created by the

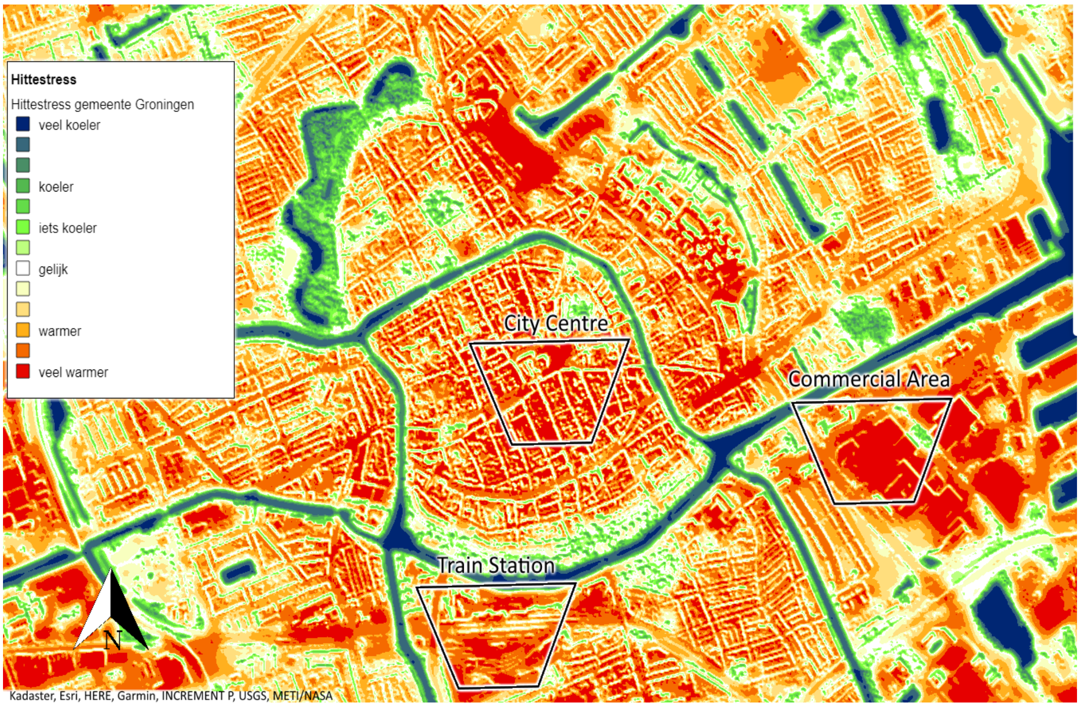

Figure 25: Heat stress in the city of Groningen (Gemeente Groningen, 2019)

University of Groningen shows that the areas around the city centre are cooled by the canals, as well as by more lush vegetation (Figure 26). The coolest areas in Groningen, according to both maps, are the city's parks. The Noorderplantsoen, which is situated on the former ramparts of the city, is situated closest to the city centre. During summer it is actively visited by city residents in search of cooling. The higher temperatures in the hotspots are the result of a lack of shading, a lack of vegetation, and a low albedo. This is especially true for both squares located in the city centres, which pop up as a hotspot on all heat maps. Lenzholzer (2008) writes that the problem of 'void' or open squares is their thermal discomfort which results from a lack of shade and thus from microclimate variation (Nikolopoulou, 2004, in Lenzholzer, 2008).

An overview map of Groningen (Figure 27) shows the location of the parks of Groningen, and marks the city centre with an A. Figure 29 shows a land surface temperature map of Groningen on the 26th of July, which is one of the hottest days on records for Groningen (KNMI, 2019). Comparing the heat map with the NDVI and building footprint allows for an interpretation of the causes of the UHI. Open areas with no vegetation are generally hot, as is the case in many of the commercial areas.

[1] Advanced Very High Resolution Radiometer from the US National Oceanic and Atmospheric Administration

Satllite image of Groningen, the Netherlands

Figure 26: Overview of the study area in Groningen

Building footprints of Groningen, the Netherlands

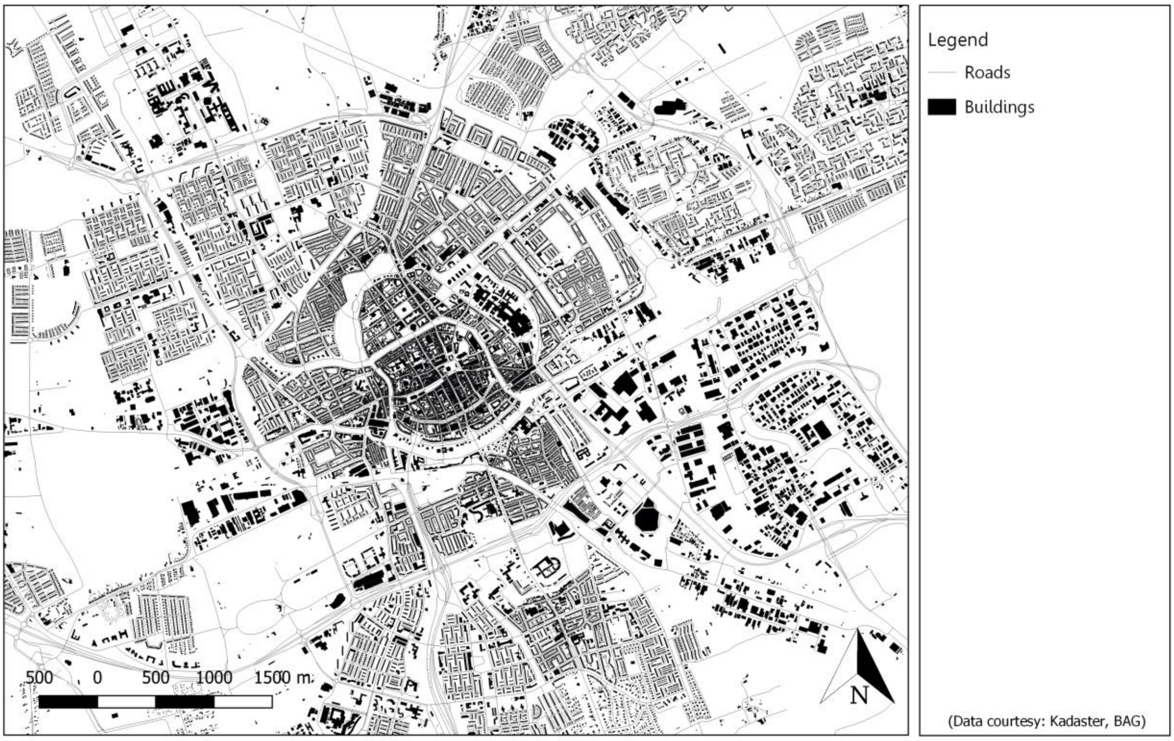

Figure 27: Building footprints of Groningen

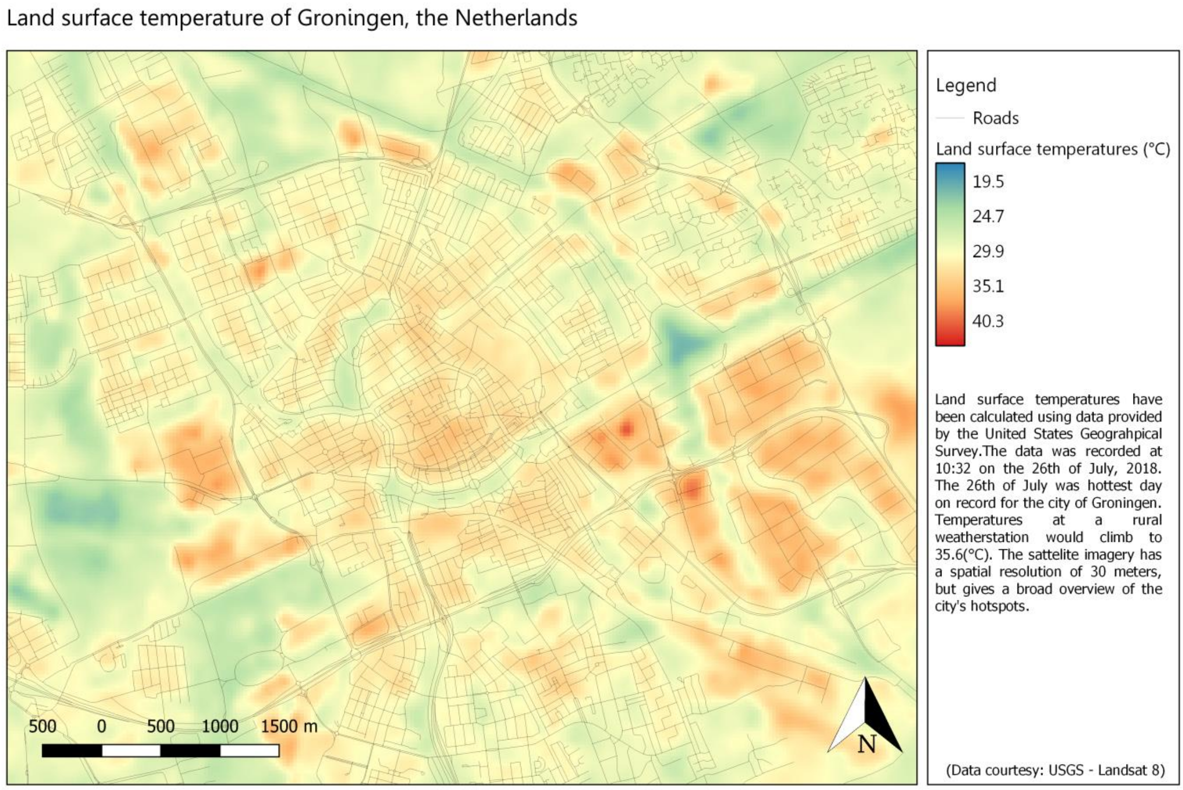

Figure 28: Land surface temperature map of Groningen

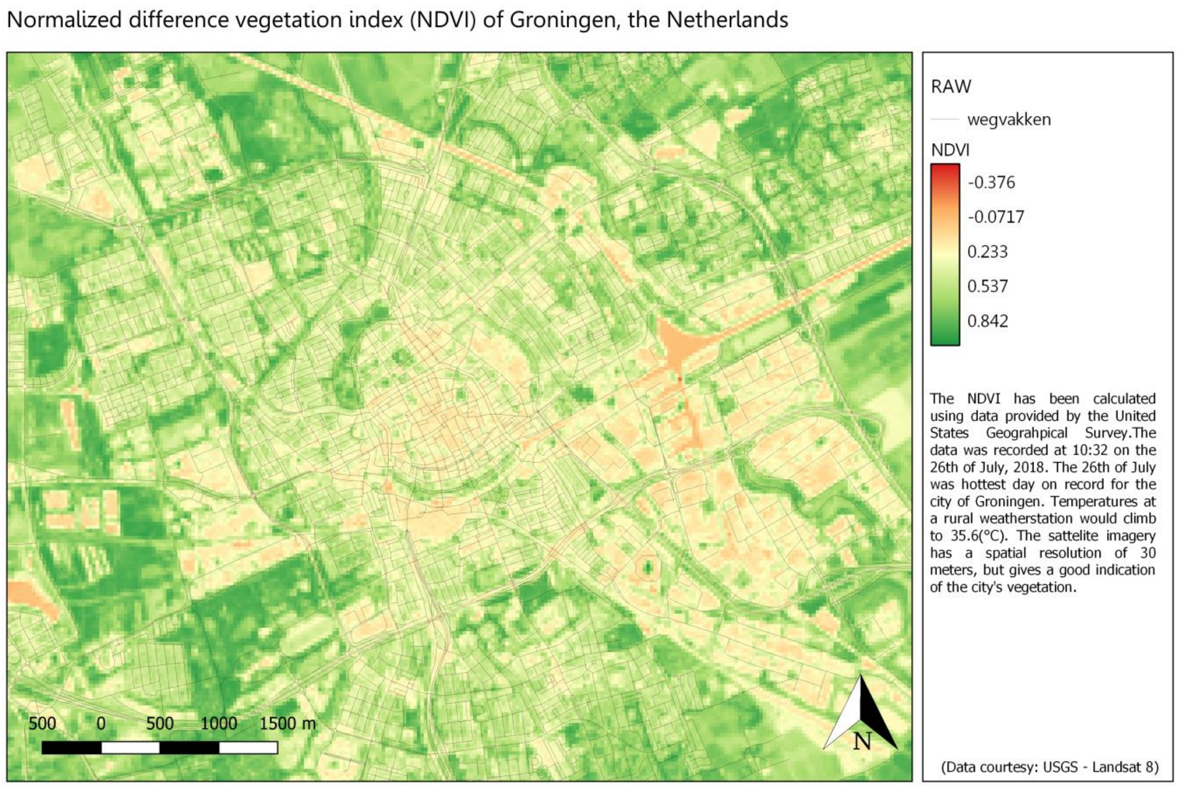

Figure 29: Normalized difference vegetation index map of Groningen

5.1.3 Climatic drivers of the UHI now and in 2050

As stated in the introduction, the intensity of the urban heat island is projected to increase as a result of global warming. According to the Royal Dutch Meteorological Institute (KNMI), the average temperature in the Netherlands will increase by 2.3°C by 2050 in the RCP8.5 scenario. This is the worst-case scenario in which minimal mitigation strategies are employed. The same scenario predicts a 17% decrease in precipitation during summers (KNMI, 2015). Less moisture will be available in the soil for evapotranspiration, leading to higher temperatures in the city. The number of nights above 20°C increases from one week per year to a maximum of three weeks per year (Klimaateffectatlas, 2014). Hot nights can have a profound effect on health. Murage et al. (2017) found that hot days which are followed by hot nights lead to higher mortality rates than when hot days are followed by cool nights. The KNMI (2017) predicts that the cooling degree days might increase from an average of 78 days a year to at least 234 in 2050 the RCP8.5 scenario. Cooling degree days are days with an average temperature higher than 17°C (Ibid.). This is likely to result in the increased use of air-conditioning units, which may contribute to an increase in the UHI.

The urban heat island of Groningen is relatively low compared to other Dutch cities because of its proximity to the sea and the higher wind speeds which are prevalent there (Steeneveld et al. 2011). However, when temperatures are above 28 degrees, the wind comes from the east much more often (Table 9). Winds from the east are much drier, while westerly winds have a moderating effect on temperatures because of the moisture they bring in from the Atlantic. Similarly, wind speeds are generally low when temperatures are high (Table 10). As such, the potential for cooling by exploiting climatological cooling mechanisms during heatwaves is limited.

Table 9: Groningen wind direction count per temperature group (1988-2018)

	Less than 16°C	16-22°C	22-28°C	28-34°C	>34°C	Total
N	415	245	112	15		787
NE	540	239	210	35	1	1025
E	769	202	239	74	5	1289
SE	418	135	132	64	2	751
S	903	350	154	35	2	1444
SW	1920	937	295	20		3172
W	1059	524	140	11	2	1736
NW	635	401	74	9		1119
	6659	3033	1356	263	12	11323

Source: KNMI - Weather station Eelde

Table 10: Groningen wind speed count per temperature group (1988-2018)

Groningen wind speed count per temperature group (1988-2018)

	Less than 16°C	16-22°C	22-28°C	28-34°C	>34°C	Total
0-1 m/s	222	136	85	29	2	474
1-2 m/s	685	463	301	68	4	1521
2-3 m/s	1068	683	414	96	3	2264
3-4 m/s	1314	727	338	54	3	2436
4-5 m/s	1135	519	160	16		1830
5-6 m/s	809	327	48			1184
6-7 m/s	649	115	7			771
7-8 m/s	346	41	3			390
>8 m/s	431	22				453
	6659	3033	1356	263	12	11323

Source: KNMI - Weather station Eelde

5.1.4 Decreasing thermal load

Of the possible planning actions related to decreasing the thermal load, Groningen only actively promotes two. One is changing the city's energy balance by building bus lanes which use reflective asphalt, and the other is to create a cooler city by adding more shade trees (Gemeente Groningen, 2016b). The greening goals of Groningen are discussed in the next chapter.

Another goal of the municipality of Groningen is to prevent urban sprawl, and to continue to build within the city limits. Densification is set to happen around stations and local centres. Shading of streets can be improved by considering their orientation, minimizing solar gains. The planned buildings should also strive to be self-shading, so outdoor and indoor areas warm up less.

5.1.5 Increasing evaporative potential

Trees and parks

In its adaptation strategy, the city of Groningen focuses mainly on greening its city. This becomes evident from both the policy documents related to adaptation and the vision document which lays out the design agenda for the city centre (Table 16 in the appendix). A strong emphasis is put on 'strengthening' park areas. For the city centre this means development will focus on greening the former city ramparts, and the canals which surround the inner city. In addition to this, the city intends to use more permeable pavements, also in its parks and along avenues which are lined with trees. Furthermore, the city prohibits the expansion of buildings into existing courtyards and gardens.

Green roofs & wadis

The city of Groningen also has a history of greening its roofs. A subsidy program has been active since 2008 (Van der Brug, 2011). By 2011, at least 180 green roofs had been constructed (Ibid.). The subsidy program is still in place and it actively promoted as a stormwater management tool and to counter the UHI.

In that same regard, the city of Groningen has been building wadis in newly constructed neighbourhoods to be able to temporarily store excess rain. These wadis also contribute to a lower

UHI because they are made of pervious materials. They function as a playground for kids when they're not filled, and usually look just like a small grass field with trees.

Stimulating the use of green roofs and planting trees are part of a wider initiative called Operatie Steenbreek. Operatie Steenbreek aims to replace impervious surfaces with gardens, ditches or permeable pavements. The goal of the initiative is to reduce the UHI, increase biodiversity, buffer water and to improve the air quality in the city. As a part of this program, residents of Groningen can trade in bricks from their garden for shrubs and small trees. They can also request to have the sidewalk in front of their house replaced with a small garden strip.

Fountain

In 2014 the municipality approved the plans to construct a fountain on the Grote Markt, the city's main square (NU.nl, 2014). The vision document shows that it is planned on the north-eastern corner of the square. As discussed in chapter 2.3.2, fountains can help lower air temperatures due to increased evapotranspiration.

5.1.6 Increasing advective cooling potential

Groningen does not actively promote advective cooling, and does not mention wind corridors in any of its policy documents. However, more trees and parks can create microclimates and generate wind flows. In its vision document it becomes clear that Groningen wishes to construct a ring of vegetation around the city centre. This could lead to an inflow of cool wind into the city's core, where temperatures are high, due to rising thermals and convective winds.

5.1.7 Reducing output and storage of anthropogenic heat

Groningen's mobility is highly sustainable, where sixty percent of all traffic movement happens by bike (Gemeente Groningen, 2018). This can in part be explained by the many students that live in the city, the short distances between amenities, and the traffic-calming measures in the city centre. Again, they are not an active policy to counter the UHI and heat stress, but they do contribute to fewer emissions and less waste heat. Groningen aims to have a carbon-neutral city centre by 2025 (Gemeente Groningen, 2018). This would cause less radiative forcing, and a cooler city centre. They aim to do this by constructing more charging points for electric vehicles and by focusing on public transport (Gemeente Groningen, 2016). Groningen does not have any light-rail services, but instead relies on buses for public transport. Many of the buses are already electric, and a pilot is running which experiments with buses powered by hydrogen (Groningen Nieuws, 2019). Already, much of the municipality's postage within the city is delivered by cyclist courier services. Green roofs and other measures which improve the insulation or decrease heat transfer into homes contribute to a smaller release of anthropogenic heat. Energy efficiency is where mitigation and adaptation meet.

5.2 Lessons for Groningen

This paragraph combines the adaptation strategies from Phoenix and Dubai and explores their possibilities for the city of Groningen. The previous chapter and section have demonstrated that the urban heat island takes on a different form in each of the three cities. Groningen shows distinctly higher temperatures in its city centre, whereas Dubai and Phoenix both have an urban cool island in their central business districts during the day. Dubai strongly benefits from an ocean breeze, where the air in Phoenix can be stifling. All three cities are ramping up their adaptation efforts, as the effects of climate change are becoming more evident. The adaptation strategies which each of the three cases employs have been summarized in three tables at the beginning of each case in the previous chapter. Compiling the strategies from Dubai and Phoenix has resulted in the following shortlist:

- Reflective roofs
- Improved building orientation
- Photovoltaic shading devices
- Wind towers
- Densification (as a means to counter the UHI)
- Shaded walkways
- Courtyards
- Misting installations

Trees and parks, green roofs and walls are not part of the shortlist, because Groningen already uses them to cool the city. Instead, the differences between Dubai and phoenix, and Groningen are listed.

The land surface temperature map combined with the heat maps made by Sweco and the municipality indicate several hotspots in the city of Groningen. Three typologies can be identified in order to structure the adaptation lessons for Groningen: 1) The commercial areas, 2) the open areas such as the squares, and 3) the highly urbanized areas.

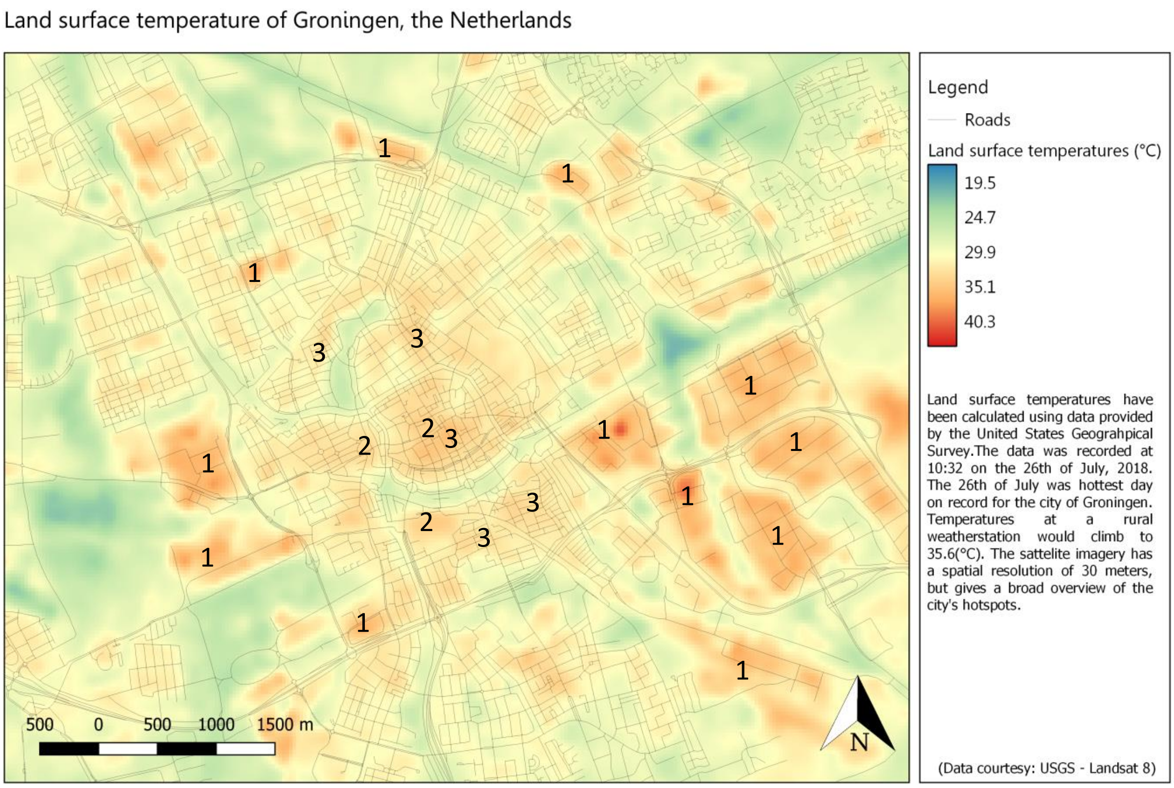

Figure 30: Three types of hotspots within Groningen 1) Commercial areas, 2) Open areas, 3) highly urbanized areas

5.2.1 Lessons for commercial areas

Decreasing the thermal load

Many of the hotspots in Groningen can be found in commercial zones, as can be observed from the figure 31. Commercial areas are characterized by a low albedo, lack of greenery, featuring a lot of impervious surfaces such as parking lots and warehouses. The materials in the commercial areas absorb a lot of heat, and the potential for evaporative cooling is low.

Commercial areas in Dubai and Phoenix also lack greenery, but have different thermal properties. Warehouses use lightly-coloured reflective roofs, which lead to lower surface temperatures (Figure 32). The cooling effects of cool roof have been proven to be quite limited on neighbourhood temperatures in Phoenix (0.5 C°C), but they form a viable alternative to green roofs. Green roofs

Figure 31: Roofs in commercial areas – pictured from left to right: Groningen, Dubai, Phoenix (Google Maps, 2019)

require more structural support, and are less fit for retrofit application to warehouses. Reflective roofs emit less heat into the air, and cause buildings to need less air conditioning to stay cool. Some of the warehouses in Groningen have already adopted reflective roofing, but it is far from common.

Interestingly, the commercial areas in Dubai appear to have a much higher density than those in Phoenix and Groningen. This could be a response to the hot climate, but may also reflect land values or Dubai's status as megacity. More research into this phenomenon may offer a conclusion on whether Dubai's commercial areas have significantly denser commercial areas, and whether it is due to the desert climate present there.

Another practice that can be imported from Phoenix is the use of photovoltaic shading devices above parking areas. Photovoltaic shading devices can help keep surface temperatures low, while also contributing to lower emissions. Lastly, permeable pavements and more trees are strategies which Groningen already uses, but which can contribute to lower temperatures in commercial areas too.

Photovoltaic shading does not have be limited to parking lots. The use of solar panels can also contribute to a lower UHI, but this was not mentioned in any of the adaptation plans of the three cities. Scherba et al. (2011) show that the addition of solar panels on black bitumen roofs can decrease amount of solar energy that is absorbed by 11%, compared to a bitumen roof without solar panels. Converting the black bitumen roof to a reflective roof would result in an 82% reduction, but adding solar panels to the reflective roof would increase the solar gains. A reflective roof with solar panels absorbs on average 55% less solar radiation than a black bitumen roof (Ibid.). The roofs in commercial areas may not be able to adequately support the solar panels, more research into the retrofit installation of solar panels is needed.

5.2.2 Lessons for the city squares and open areas

Decreasing the thermal load

There are a number of open spaces in Groningen which have relatively high surface temperatures. The most noticeable hotspots are the two main squares in the city centre and an area due west of it, called the Westerhaven, as well as the marshalling yard behind the train station and the square in front. The areas are characterized by a large H/W ratio, and few shade trees. A potential strategy to lower urban temperatures is the use of reflective paving. They can be especially useful in areas which are not frequented by pedestrians. This is because the reflected radiation contributes to a higher "feels like" temperature, which contributes to a decrease in thermal comfort.

Adding shading by decreasing the H/W ratio of the squares by adding more buildings because both squares in the city regularly host city markets and other events. However, there are plans to remove the marshalling yard south of the train station, and to replace it with high-density development, which could lead to lower temperatures.

Groningen already uses trees to provide shade and evaporative cooling, but can consider artificial shading devices in pedestrian areas. Shading devices in Dubai and Phoenix take on different forms, organic or otherwise, and can feature solar cells (Figure 33). The benefit of shading devices as explained by Golden et al. (2007) is that their performance is not affected by drought, as compared to trees. A drawback is that they also block the sun in winter, when temperatures are much lower. Nonetheless, there are shading devices which can be taken down in winter.

Figure 32: Shading devices in Dubai and Phoenix - Pictured from left to right Xeritown, Dubai Island Bluewaters, Roosevelt Row Arts District (Construction Week Online, 2009; The National, 2018; Porter, 2015)

Advective and evaporative cooling measures

Another measure to mitigate is the use of wind towers. Traditional wind towers rely mostly on wind to provide cooling, but modern designs also use an evaporative component. Water is sprayed into the air at the top of the tower, and cools the air. The cooler, moist air sinks because of its higher density, and is allowed to evaporate. Air leaving the tower can be as much as 8 °C cooler than the ambient air temperature surrounding the tower (Soutullo, Sanjuan, & Heras, 2012). A new neighbourhood of Masdar City in Abu Dhabi saw the construction of an evaporative wind tower on a central square (Figure 34) (Ibrahim, 2016), and Madrid has constructed one on its ‘Eco-boulevard’ (Soutullo, Sanjuan, & Heras, 2012). The wind tower in Madrid uses fans and solar panels to achieve cooling when wind speeds are low, and therefore also works during heat wave conditions Sanjuan, & Heras, 2012). The installation of evaporative misters on the square may also be effective at lowering the temperatures on the squares.

Figure 33: Modern windtower at Masdar City (Masdar Official, 2010)

5.2.3 Lessons for the highly urbanized areas

Decreasing the thermal load

Figure 34: Roofs in the city centre of Groningen (Google maps, 2019)

The city centre of Groningen is densely packed with a lot of stores and houses, and does not feature a lot of green. The municipality already aims to add more green space by planting more trees and promoting the use of green roofs. Other adaptation strategies are hardly considered.

Decreasing the thermal load by increasing the albedo of roofs has a lot of potential, because of the high building density of the centre of Groningen (Figure 35). The roofs seen in the image are representative of many neighbourhoods of Groningen, in the sense that they use asphalt roofing when roofs are flat. For example, the use of reflective surfaces to replace the large area of asphalt roofs may help to reduce surface temperatures in the city centre. As stated before, the contribution to air temperatures at the neighbourhood level was found to be low in the city of Phoenix. However, phoenix is also characterized by wide streets, and buildings of uniform height. Roofs form a larger share of the total amount of surfaces in Groningen than in Phoenix, which means the contribution of reflective roofs may also be larger. Buildings in Groningen are also less homogenous than the ones in Phoenix. While the benefits to the urban heat island may be limited, but the contribution to people living in the houses can be large. Less heat is transferred into the homes, contributing to more thermal comfort. Less air conditioning is needed, contributing to lower anthropogenic heat release. Green roofs are not always an option on buildings in these areas.

Figure 35: Shading in Dubai and Madrid – pictured from left to right: Historical Souk in Dubai, shading in a shopping street in Madrid (What's On, 2014, Porter, 2015)

Another strategy of reducing the radiation that is received by the streets in the city centre is by adding more shading. The centre of phoenix is shaded by high-rise, which is why surface temperatures are lower there. Similarly, a combination of tall buildings and narrow streets offer shade to streets in Dubai. However, Dubai also uses shaded walkways to provide lower surface temperatures in the street. Fewer surfaces are exposed to sunlight and reflected shortwave radiation. While the traditional covered souks of Dubai might not be useable for Groningen, the concept of providing more shading in its shopping streets is. Permanent structures like those in Dubai might be suitable for climates where temperatures never drop below 20℃. Figure 36 shows an example from Madrid which may be better adapted to the Netherlands, because it is easier to take down in winter. Increasing the evaporative cooling potential in dense neighbourhoods can be achieved by installing misting fans. A large benefit of misting fans is that they do not take up a lot of space, whereas a fountain or pool can be a hindrance to pedestrians.

5.3 Discussion

The last paragraph introduced several strategies which are common in Dubai and Phoenix, but have not yet found their way into north-western Europe. It can be argued that the climate responsive design strategies have not been transferred because the climates are simply too different from each other. Another explanation can be that north-western Europe is unfamiliar with the concepts, or too unsure of the benefits. This is not surprising, because northern Europe does not deal with extreme heat year/round.

For this reason, adaptation strategies for northern Europe should always consider the negative impacts they might have on the city during colder periods. The use of reflective roofs was suggested for Groningen. Reflective roofs can lower air temperatures in the city, but may result in higher heating costs. Much of norther-western Europe has a moderate climate, where demand for heating is still high in winter (Kolokotroni et al., 2013). Reflective roofs are a measure mostly aimed at lowering cooling costs. astrapostoli et al., (2014) investigated the effect of a cool roof on the cooling and heating loads for an industrial building in the south of the Netherlands. They increased the albedo from 0.3 to 0.67 through the use of a cool coating. Annual cooling loads were found to decrease by 73% and heating loads increased by 5%. Outdoor temperatures were not measured. Regardless, a comparable study in London found that air temperatures could be reduced by 2 CELSIUS, sugge reflective roofs can make a contrisbution to lowering the urban heat island (Kolokotroni et al., 2013). The study in london showed that heating costs can increase by up to 10%. This difference may be explained by the fact that the building in the netherlands was an industrial building where more waste heat is produced by machines.

A more detailed study should be conducted to investigate the effects of cool roofs on the urban heat island of Groningen, and on the energy performance of residential homes. Cool roofs may become more cost-effective, because the cooling loads in Groningen are expected to increase as a result of climate change (Spinoni et al., 2017). Conversely, heating loads are expected to decrease.

The retrofit installation of reflective roofing can mitigate the urban heat island where green roofs cannot. This is because reflective roofs don’t need additional support. Green roofs are generally also more expensive than reflective roofs, which further limit green roof potential. However, the municipality of Groningen is only pushing for the implementation of green roofs (Gemeente Groningen JAARTAL)X3, and is missing out on the cooling potential of reflective roofs.

Perhaps more importantly, cities should always try to limit their carbon footprint. Carbon emissions are the indirect cause of increased heat, and adaptation is the fight against the symptoms of this larger problem. For this reason, climate adaptation and mitigation should strive to look for synergies.

Roofs are one of the arenas in which this is possible. The use of solar panels on white or green roofs improve the thermal performance of roofs compared to a black bitumen roof, while also contributing to a transition to cleaner energies.

For newer developments, Groningen plans to further densify urban areas. New development can benefit from higher H/W ratios as they are show to have lower surface temperatures. Improved building orientation can also help reduce solar gains. A strategy related to this is building sloped roofs, which angle downwards to the north. Self-shading buildings like these have lower cooling costs and emit less long-wave radiation. If they are equipped with reflective roofs, this effect is enhanced. The aforementioned strategies are also likely to lead to higher warming costs in winter. A cost benefit analysis of heating costs under climate change can conclude whether they are a viable option. The use of courtyards in new developments is another strategy which can limit the urban heat island. Courtyards offer shade and can be equipped with vegetation, water basins or fountains to absorb solar energy through a latent heat flux. More vegetation and fountains are already a part of Groningen's adaptation strategy, but actively pushing for shaded areas in new developments is not. Taleghania et al. (2014) state that courtyards can be a viable adaptation strategy in the Netherlands. They found that courtyards in the Netherlands which are oriented along a North-South axis receive the least amount of sunshine, and consequently have lower temperatures. Using highly reflective paint on the facades leads to an increase of mean radiant temperature, whereas planting vegetation or constructing a fountain leads to lower temperatures in the courtyard.

Another adaptation measure which is rarely seen in north-western Europe, if at all, is the wind tower. Rahola et al. (2009, p 23) write that evaporative wind towers "are seen as a really promising option for moderate climates". However, this relates to cooling inside a building, and not much is known about how they would perform in north-western Europe. A likely drawback of evaporative wind towers in north-western Europe is that they are likely to only serve a purpose in summer, or during heatwave conditions. An exploratory study of the performance of a temporary evaporative wind tower in the Groningen may pave the way for its further implementation.

While the urban heat island is the object of study of this thesis, thermal comfort should be an important consideration in urban planning. The foremost aim of making changes to the urban environment should be to improve the lives of those who inhabit them. As such, lowering urban temperatures through the use of reflective paving would result in decreased thermal comfort, and perhaps higher morbidity and mortality rates. In that same regard, the use of misting fans improve thermal comfort, but are likely to have a limited effect on the urban heat island at the meso scale. They are especially effective at improving thermal comfort at the micro scale (Wong & Chong, 2010). However, the literature does not give any insights in their effect on the urban heat island on a wider scale. More research into the effectiveness of misting fans in Groningen or in moderate climates is needed. Misting fans are especially effective in dry climates, and offer less cooling under conditions of high humidity (Wong & Chong, 2010). High humidity also produces more bacteria and fungi (Ibid.). The impact of the Dutch climate on the performance of misting fans in an urban environment has not yet been researched (as far as I can tell).

6. Conclusion and Reflection

6.1 Conclusion

The objective of this study has been to identify lessons for Groningen by examining the response of Phoenix and Dubai to their urban heat island. The research question “*What are the current evidence-based adaptation strategies currently used in Phoenix and Dubai to counter the urban heat island and can they be applied to Groningen?”* guided the research. Dubai and Phoenix are both cities who have been dealing with extreme heat for decades, if not centuries.

Five different adaptation strategies were identified. Exploiting climatological cooling, reducing the thermal load, increasing the evaporative cooling potential, increasing the advective cooling potential, and reducing the output of anthropogenic heat. Adaptation measures can provide cooling through one or more of the mechanisms described above.

Dubai benefits from climatic cooling in the form of a mountain or sea breeze may provide cooling. Groningen is unlikely to benefit from a sea breeze during heat wave conditions, because of low wind speeds and hot easterly winds.

Dubai and Phoenix reduce the amount of solar radiation that is stored in the city through the use of high albedo surfaces and added shading. The use of reflective roofs, or cool roofs, is common practice in Phoenix, whereas black bitumen roofs are typical of Groningen. Because winters in Groningen are likely to get warmer, the heating penalty of cool roofs in winter is likely to diminish. As a result, reflective roofs may become more cost-effective and popular. When used in conjunction with solar panels, reflective roofs are still cooler than bitumen roofs. Less air-conditioning is needed, which has been shown to contribute to the UHI (Ohashi et al., 2007). Shading is provided by denser urban forms in Dubai’s old town with high H/W ratios. Similarly, Phoenix downtown area is cooler because of the shade provided by its highrise. Improved building orientation causes buildings to be self-shading, and buildings consequently emit less heat into the environment. Photovoltaic shading canopies are used in the parking lots of Phoenix to achieve lower air temperatures. They were found to be more efficient at reducing air temperatures than trees. Groningen can also benefit from these car ports with solar panels. Middle Eastern architecture uses courtyards to provide a cooler urban environment. Courtyards can also be effective in a Dutch climate, as evidenced by Taleghani et al. (2014). Cooling in these courtyards can be improved by adding vegetation or bodies of water. Using reflective paving or coatings on the walls inside the courtyards will result in lower surface and air temperatures, but higher mean radiant temperatures. Mean radiant temperatures negatively impact thermal comfort. For this reason, reflective coatings should predominantly be used in areas which are not often visited by pedestrians. Using shading is a more viable strategy there.

All three cities are cooling their cities through the use of evapotranspiration. They construct parks and plant more trees. Vegetation uses a fraction of the incoming solar energy for photosynthesis, and for evapotranspiration. As a result, temperatures are lower. Vegetation can also provide shade, which also contributes to lower temperatures. Phoenix uses xeric, drought-resistant landscaping to save water, while also contributing to lower temperatures. They are less efficient at cooling than fully vegetated, mesic landscaping. Shade trees provide the most cooling in both types of landscaping. While green roofs are promoted in all three cities, they were found to have a limited effect in Phoenix and Dubai.

The fourth strategy of providing cooling in an urban environment is through the use of advective flows. Wind towers and evaporative misters may be able to provide cooling in Groningen. Wind towers and misting fans create breezes which can offer additional cooling because of moisture. The moisture, which is allowed to evaporate, lowers the temperatures of the advective flows. These adaptation measures may be effective during summer, but are likely be of less use during winter in Groningen. Temporary installations during heat waves can be an adaptive response to heat waves.

The same considerations are true for the other adaptation measures. Permanent shading devices can incur more heating costs in winter, which is likely to result in higher outputs of emissions. Vegetation trumps artificial shading in this regard, as they shed leaves in winter. However, vegetation may perform less after long periods of drought.

The municipality may be wise in exploring more ways to adapt to heat in addition to greening measures. It could do so by creating test grounds for the aforementioned adaptation strategies, or by constructing temporary test-installations in the city. The test installations could serve a double function by educating citizens on climate change and how to adapt their homes to it. They may form interesting meeting spaces, as was done in Madrid's Eco Boulevard.

6.2 Reflection

The thesis sets out to explore the differences between Groningen, Dubai and Phoenix, with the aim of learning from both desert cities. Even though the thesis does not present entirely new adaptation strategies, it does illustrate that Dubai and Phoenix use additional adaptation measures on top of greening which are not yet considered in Groningen's adaptation plans. While there is reason to believe that the adaptation strategies used in Dubai and Phoenix can be successful in Groningen, further studies could research in-depth whether the 'additional' measures are cost-effective year-round. This also depends on the climate scenario's which are to be released by the KNMI in 2021.

The thesis could have focused more on the anthropogenic heat release. However, this is largely a field of energy efficient homes and passive cooling designs. Including everything from this discourse is outside the scope of the thesis. However, there are obvious gains to be made in this field. Buildings with a higher thermal mass stay cooler, and the addition of external shading can prevent houses from overheating. A study by Raji et al. (2016) already investigates this, who investigated the energy efficiency of high-rise by changing the building envelope. For example, they suggest a wall to window ratio of 50%, and the use of external shutters. Adjustable shadings with a summer schedule yield the highest benefits to cooling and heating loads. For Dubai, this aspect of urban heat island mitigation could have been more expansive.

The maps that have guided the personal observation could have been given a more prominent role in the thesis. While they have confirmed that the parks and downtown areas of Phoenix and Dubai are cooler, they aren't directly linked to the adaptation strategies. Close-up temperature comparisons could have increased the thesis credibility. However, the conclusions would not have been very different. The cool spots on the surface temperature maps would show parks and neighbourhoods with mesic landscaping, or the downtown areas with a lot of shade, or reflective roofs. A smaller research area could have made for a more consistent research strategy by narrowing the scope, and would have allowed for more generalization. For example, three areas of one square kilometre could have been observed more in-depth. A generalization is made that 'generic' buildings in Dubai do not use shutters, which is in line with literature. However, all of Dubai is too big to view with Google Street View.

The thesis has shown the potential lessons for Groningen. Further research should indicate whether professionals are actually using the adaptation measures discussed in this thesis, and to which extent the climate requires them to do so.

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7. Appendix

7.1 Sources for Dubai

Table 11: Academic sources for Dubai

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Taleb, D. and Abu-Hijleh, B. (2013). Urban heat islands: Potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE. *Renewable Energy* **50**:747–762. doi: https://doi.org/10.1016/j.renene.2012.07.030.

Table 12: Non academic sources for Dubai

Title	Author	Year	Key subjects	Source type
Dubai Receives Platinum Rating in LEED for Cities	Gulf News	2019	Sustainable building	News article
***Dubai Metro Completes Five Successful Years*.**	Guld News	2014	Sustainable mobility	News article
Green building guidelines, UAE.	Government of Dubai, Ministry of Public Works and The Ececutive Council	2009	Green building guide	Policy document

7.2 Sources for Phoenix

Table 13: Academic sources for Phoenix

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Table 14: Non academic sources for Phoenix

Title	Author	Year	Key subjects	Source type
Phoenix is trying to fight deadly heat — and we should all take note.	Vice news	2018	Evaporative cooling at a busstop	News article
Keeping downtown Phoenix cool: A look inside the underground water-chilling plant.	FOX news	2017	District cooling (adaptation strategy)	News article
Cool urban spaces project	City of Phoenix	2014	Adaptation strategies, evaluation	Policy document
Phoenix International Green Construction Code - CHAPTER 4 - SITE DEVELOPMENT AND LAND USE https://codes.iccsafe.org/content/chapter/390/	City of Phoenix	2011	Sustainability certificate	Building code
The Tree and Shade Master Plan	City of Phoenix	2010	Adaptation strategies	Policy document
Downtown urban form project	City of Phoenix	2008	Adaptation strategies	Vision document

7.3 Sources for Groningen

Table 15: Academic sources for Groningen

Brug, van der, S. (2011). *Groen Op Niveau: Een evaluatie van de subsidieregeling van de gemeente Groningen voor het aanleggen van groene daken.* Groningen: Dienst Ruimtelijke Ordening Economische Zaken.

Table16 Sources for the adaptation strategies of Groningen

Title	Author	Year	Key subjects	Source type
Geoportaal Gemeente Groningen – Energie & Duurzaamheid	Gemeente Groningen	2018	Climate risk	GIS map
Stresstest Groningen & Ten Boer	Gemeente Groningen, Sweco	2018	Climate risk	Policy document
Plan van aanpak Klimaatadaptief Groningen	Gemeente Groningen	2017	Adaptation strategies	Policy document
Leidraad voor de openbare ruimte van de binnenstad van Groningen	Lola landscape architects, Topotek 1, Gemeente Groningen	2017		Vision document
Groningen Klimaatbestendig	Gemeente Groningen	2016	Adapatation strategies	Policy document
Klimaateffectatlas	Stichting Climate Adaptation Services	(Based on KNMI data from 2014)	Climate risk	GIS map

The Plan van Aanpak Klimaatadaptief Groningen gives the most comprehensive overview of the planning actions which are currently in place to counter the UHI. The Groningen Klimaatbestending document which shows where they are already implemented, while the vision document shows where we might expect adaptation measures to be implemented in the future.