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Outdoor thermal comfort in Drottninghög, Helsingborg
A study on the effects of urban densification in a warmer climate

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Bachelor thesis, 15 credits, in *Physical Geography and Ecosystem Analysis*

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Abstract

Extreme heat can lead to a significant increase in mortality, especially for urban citizens. Densification of urban areas can dramatically affect the local climate of the city by replacing green areas with impermeable materials and changing both radiative and turbulent fluxes. The assessment of the thermal comfort in urban areas is an important consideration for local municipalities to mitigate zones of extreme heat and to use in climate adaptation strategies. In Drottninghög, a district in Helsingborg, the urban thermal comfort can change dramatically as the area will be densified with over 1100 apartments through the construction of multi-story buildings. The aim of this study is therefore to study the consequences of the future building situation in Drottninghög for a normal summer and an extremely warm summer, using the model SOLWEIG, which computes the mean radiant temperature (T_{mrt}), a variable commonly used to assess the thermal comfort of humans. Future scenarios are considered using two different future scenarios with a 2°C and 3.5°C summer temperature increase by the end of the century. The increased mortality risks are assessed by computing the number of hours with an increased risk. The effect of increased tree cover is also evaluated as a potential mitigation strategy. The results indicate that open areas are more susceptible to high values of T_{mrt} with a paved schoolyard and a market square experiencing the most hours with an increased health risk. The future buildings situation leads to some of the parking lots being replaced, causing the T_{mrt} to decrease. The multi-story buildings create significant shade leading to lower T_{mrt} as a result of less incoming radiation. An extreme summer has a T_{mrt} daytime average of 6°C warmer than a normal summer for the months June to August. The future scenarios lead to an increase in T_{mrt} similar to the increase air temperature. The addition of trees causes a decrease of T_{mrt} by 10°C for open areas and can be regarded as an appropriate mitigation strategy. The findings of this study assess the thermal environment in the study area in regard to radiation patterns and can aid the decision makers in future plans for the district. However, future studies should include wind patterns as it would further improve the evaluation of the influence of constructing tall and dense buildings in Drottninghög, as well as incorporating the cooling effects of wind in regard to outdoor thermal comfort.

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1 Introduction

More than half of the world's population live in urban areas, in Europe the figure is even higher with three quarters of the population in cities (UN 2018). These figures are projected to increase, with urbanization in the world set to go up to 68 percent, compared to the levels of 1950 when only 30% lived in urban areas (UN 2018). This dramatic change means that there is a great need to build enough houses to be able to cope with the increasing urban population. Increasing populations in urban areas often lead to green areas such as parks being replaced with buildings and impervious materials resulting in more densely built cities. Replacing green areas with impervious ground cover can dramatically affect the climate in cities (Roth 2012). Heavy precipitation can cause severe floods when paved areas replace grass and bushland, the biodiversity can decrease as natural habitats are removed, and the temperature might increase substantially (Oke et al. 2017). Another consequence of further urbanization is associated with the construction of multistory buildings. Tall buildings can substantially affect the thermal environment in a city by creating shade and disturbing wind patterns (Oke et al. 2017).

In a changing climate, urban areas will not only be affected by increasing populations, but the cities will also experience increasing temperatures. The temperature in the worlds urban areas will still increase with a maximum 2°C even if high mitigation against global warming is taken (Revi et al. 2014). If no mitigation action is taken, temperatures could rise by at least 2.5°C in 2100 without taking the urban heat island into account (Revi et al. 2014). The urban heat island is a phenomenon that results in cities having a higher temperature than the surrounding rural areas. Higher latitudes will experience an even greater increase in temperature, where a mean rise of 3.5°C is expected at the end of the 21st century if no mitigation is taken (Revi et al. 2014). Taking into account the urban heat island effect the temperature can in some cases increase above 5°C compared to preindustrial levels (Revi et al. 2014). The increasing temperatures will also mean a higher frequency of heat waves. In Sweden, the Swedish Meteorological and Hydrological Institute (SMHI) predict that extreme heat waves can occur every 3-5th year by the end of the century instead of the current frequency of every 20th year (Persson and Wern 2011). A heat wave is defined in various ways, and no unifying international definition exists. According to the World Meteorological Organization a heat wave is defined as a period of five consecutive days with a maximum daily temperature of 5°C above the season average, defined for the period 1961-1990 (Persson and Wern 2011). SMHI have a different definition where a heat wave occurs when the daily maximum temperature reaches above 25°C for five consecutive days (Persson and Wern 2011). Urban heat islands can amplify the effects of global warming in cities, causing prolonged and more intense heat waves (Hoegh-Guldberg et al. 2018).

The consequences of an intense heat wave can be disastrous for the urban population. In the year 2003, a heat wave struck Europe and led to over 15 000 deaths in France alone due to the extreme heat (Persson and Wern 2011). In 2018, Sweden suffered one of the warmest summers in over 200 years. The temperature levels were 2-4 °C higher than normal in the southern parts of the country (SMHI 2018). The number of fatalities was estimated to be 600 across Sweden due to the extremely warm weather (Åström et al. 2019). During the warmest week in July (16th-22nd) the increase in mortality was 13.5% (Åström et al. 2019). Increasing temperatures especially affects the urban population, with several studies showing a correlation between heat waves and increased mortality in urban areas (McMichael et al. 2006; Tan et al. 2010; Venter et al. 2020). The Tan et al. (2010) study of Shanghai showed that the heat waves are more frequent but also more prolonged in the city center compared to rural areas. This resulted in higher number of deaths in the city center compared to rural areas, especially for two intense heat waves. Relief at night is discussed as one of the main causes of lower mortality rates in rural areas compared to urban areas. The night temperature remains high in the city while people in the rural zone experience a cool night in comparison (Tan et al. 2010).

A study by Rocklov and Forsberg (2008) performed in Stockholm compared daily mean temperature for the period 1998-2003 with the number of cardiovascular and respiratory fatalities. It showed an increase in mortality during heat waves, with higher risk for older people with respiratory or cardiovascular diseases (Rocklov and Forsberg 2008). The elderly are also more affected by a heat wave due to changes in the regulation of body temperature (Koppe et al. 2004). Additionally, the health risks of heat waves are related to fitness and socioeconomic status of the individual. Low income persons living alone are also identified as a vulnerable group (Koppe et al. 2004).

In a study by Oudin Åström et al. (2018), the mortality rates in different parts of Sweden were compared. Mortality rates in northern cities such as Luleå, Umeå and Sundsvall increased at a lower temperature threshold than in the south of Sweden (Oudin Åström et al. 2018). The difference in adaptation to extreme heat between regions has been studied in both the USA by Kalkstein and Davis (1989) and in Europe, in relation to the heat wave of 2003 by Le Tertre et al. (2006). Their studies showed that regions that experience fewer heat waves and extreme temperatures are less adapted to increasing temperatures and the mortality risk increases at a lower threshold.

Some of the main mitigation strategies to avoid higher temperatures in cities involve changing the urban geometry by building more densely and with greater height, as well as changing the direction of the buildings. Changing the urban geometry can lower the temperature in a city the most compared to other strategies such as planting of trees incorporating water bodies and using building materials with a higher albedo. (Lai et al. 2019)

Another way to mitigate the increasing mortality levels during heat waves is to cool houses with for example air-conditioning. However, increasing electricity consumption during a heat wave could be a concern for local municipalities and cities.

In a study in Australia by Hatvani-Kovacs et al. (2016), the electricity consumption during a heat wave stood for one fifth of the yearly demand of electricity in Adelaide, Australia. Besides increased electricity consumption, water demand also increases during a heat wave (Rinaudo et al. 2012), showing that the impacts of a heat wave are often interwoven, water and electricity shortages can increase the health risks within vulnerable groups, which in turn can add to the high mortality rates already caused by the extreme temperatures (Zuo et al. 2015).

The mortality and risk levels of increased heat are usually quantified by measuring the human thermal comfort. It is determined by the air temperature, humidity, wind and absorbed radiation energy. A common variable to measure the outdoor thermal comfort is the physiologically equivalent temperature (PET). PET uses inputs of vapour pressure, wind speed and air temperature and mean radiant temperature (T_{mrt}) to determine outdoor thermal comfort on a standardised standing person. Of these T_{mrt} (defined below) has the strongest influence on PET during clear summer days especially in urban environments. (Mayer et al. 2008). Due to its large influence on the thermal comfort of humans, I have selected the T_{mrt} to assess the outdoor thermal comfort in this study.

2 Aim

The aim of this study is to evaluate the outdoor thermal comfort in Drottninghög, a district in the city of Helsingborg, for a normal and an extreme summer. In order to assess the human thermal comfort, the mean radiant temperature will be computed for daytime conditions. Thermal comfort in future scenarios will be analyzed by considering a warmer climate and future building plans in the study area. Lastly, the impact of new buildings and the role of trees will be analyzed for a small area in the southwest part of Drottninghög.

Research questions:

1. How could future buildings plans change the outdoor thermal comfort in Drottninghög, for a normal and an extreme summer, in a warmer climate?
2. How could the increasing temperatures in a warmer climate, for a normal and an extreme summer, affect the heat related mortality risk?
3. Is increasing the tree cover in future building plans a good mitigation strategy to lower T_{mrt}?

3 Background

3.1 Urban heat island

The urban heat island effect has implications for the thermal environment in a city and thus the thermal comfort of its citizens. The urban heat island effect is a clear modification to the local climate of a city. It occurs in every city leading to a different climate compared to the surrounding areas (Roth 2012). It is defined as the difference between the maximum temperature in the city and the temperature in the surrounding area (Oke et al. 2017). However, the variation of the temperature within a city is great and the urban heat island can substantially differ depending on the measurement location within the city. Parks and other green areas tend to be cooler zones within cities while impermeable structures such as paved roads and buildings lead to higher temperatures (Oke et al. 2017).

The urban heat island can affect the climate in the city on different vertical scales. A difference in temperature can be seen in the subsurface with temperatures being higher in urban areas than rural. This pattern can also be seen high up in the atmosphere with a boundary heat island being present up to a couple of kilometers altitude. Closer to the surface, where thermal comfort is measured, there are two different heat islands considered. Firstly, the surface heat island, which is the temperature difference at the surface of a material between a rural area and an urban area. Secondly, the canopy heat island, which is the temperature difference in the air volume inside the cities, specifically to the top of buildings and trees. (Oke et al. 2017)

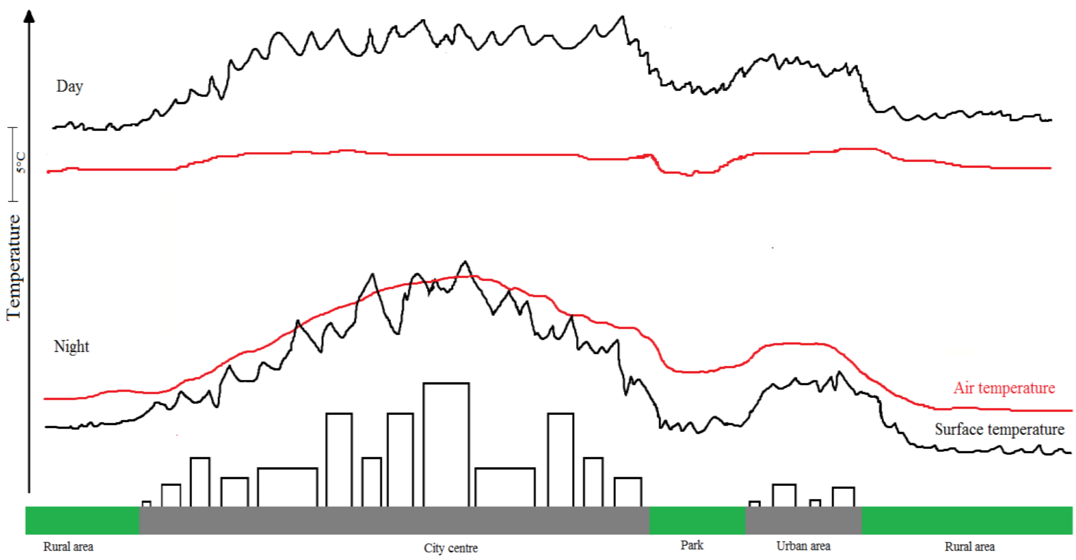

Figure 1. Schematic graph, illustrating surface temperature and air temperature for a day respective night through a cross-section of a city and its surroundings. Modified from Oke et al. (2017)

The urban heat island effect varies during the day and is different for the different types. As seen in Figure 1, the surface heat island is higher during day compared to the canopy heat island. During the night the two urban heat island types are more similar. This is typical for the urban canopy island which is mainly a nocturnal phenomenon caused due to lower cooling rate in cities compared to rural areas. The highest difference in the canopy heat island therefore occurs on calm nights where the advection is low (Oke et al. 2017). For surface heat island the minimum during the day is reached a couple of hours after sunrise as the warming is slower in urban areas as a result of shading and the surface thermal properties (Oke et al. 2017).

3.2 Determinants of temperature in urban and rural areas

The difference in temperature between a rural area and an urban area results mainly from changes in the convective, radiative and turbulent fluxes, altering the surface and air volume energy balance (Oke et al. 2017). A changed ground cover alters the thermal properties of the surface meaning the thermal conductivity and the capacity to store heat will be changed (Oke et al. 2017). Materials that are poor thermal insulators can be very hot during the day as they do not conduct or diffuse the heat out from the material. Buildings materials usually have a greater heat storage capacity and can later release the heat during the night (Roth 2012). The radiative properties of the surface are also an important driver behind the increased temperatures in urban areas. Materials with lower albedo such as most building materials and paved areas reflect less shortwave radiation which result in a greater proportion of the shortwave radiation being absorbed (Oke et al. 2017). A higher albedo value could lead to lower surface temperatures. However, the increased reflected radiation could increase the radiation heat absorbed by pedestrians (Chatzidimitriou and Yannas 2015).

Replacing vegetation with paved areas or buildings can result in a difference in the latent heat flux. The evaporative cooling of the vegetation leads to lower temperatures but also smaller differences between day temperatures and night temperatures (Oke et al. 2017). A decrease in latent heat flux is closely related to impermeable materials acting as a waterproofing (Roth 2012). The less soil moisture in urban areas means the evaporation rate is decreased resulting in higher temperatures. Due to its low reflectivity and high thermal capacity water bodies can be heat sinks in a city with temperatures lower than paved areas (Chatzidimitriou and Yannas 2015). Additionally, evapotranspiration lowers the surface temperature of the object resulting in less longwave radiation being emitted (Chatzidimitriou and Yannas 2015). A study in Toronto by Wang et al. (2016) showed that a 10% increase in vegetation can decrease the temperature by up to 0.8°C and the mean radiant temperature by up to 8.3°C. The introduction of vegetation on roofs can also influence the thermal environment in a city. Green roofs can reduce the temperature, but only if implemented at a building at a height of maximum 10 meters from the ground surface (Berardi et al. 2014). Green roofs higher than this have shown to not have a substantial effect on the thermal comfort of humans (Lai et al. 2019).

The geometric properties of a city are also an important factor behind the microclimates in a city. The creation of street canyons in between tall and densely built buildings is a common scenario in large cities. Tall and densely located objects can both provide shade for a surface leading to lower incoming shortwave radiation and reduce the amount of outgoing radiation as walls absorb the radiation (Roth 2012). Direction and openness to the sky can lead to surfaces experiencing different amounts of incoming shortwave radiation (Oke et al. 2017). The sky view factor is commonly used to determine the openness to the sky and thus the incoming shortwave radiation (Roth 2012). During daytime, a densely built area with a low sky view factor such as a street canyon has a lower temperature compared to a more open area. However, during nighttime open areas have shown to cool off at a higher rate due to a higher loss of longwave radiation (Chen et al. 2012)
Tall and dense objects can additionally disturb the turbulent fluxes. Surfaces sheltered from wind result in less advection and convection of heat (Oke et al. 2017). Street

canyons can in that case both provide shade which lowers the surface temperature, but also lower the advection cooling from wind and the outgoing longwave radiation. Even though advection cooling has an effect on the thermal comfort, the influence of reduced wind speeds is less than that of increased shade. Andreou (2013) found that the effect of shade is higher than the effects of decreased wind speeds. The study also showed that the direction of the buildings is an important factor in differences between different street canyons. With street canyons facing an east to west direction being more susceptible to higher temperatures than north to south facing street canyons due to higher exposure to solar radiation for east to west street canyons.

The anthropogenic heat flux is also important to take into account when comparing urban areas to rural areas. The emission of heat from industries, buildings and traffic add to the already increased heat due to changes in the energy balance. In a study in Tokyo by Chen et al. (2009) the release of heat from air-conditioning and traffic notably affected the temperature in a narrow street canyon. Besides the release of heat from anthropogenic sources the emission of air pollutants can lead to more outgoing longwave radiation being absorbed and later reemitted to the surface (Roth 2012).

3.3 Mean radiant temperature

Mean radiant temperature (T_{mrt}) is defined as the homogenous temperature of an imaginary enclosure where the radiant heat from the human body equals the one in the nonuniform enclosure (Owen et al. 2009). T_{mrt} is dependent on the direct and diffuse solar radiation, and the reflected shortwave radiation from surrounding objects (Kantor and Unger 2011). It is also influenced by the downward longwave radiation from the atmosphere as well as the longwave radiation from the surrounding objects such as buildings and walls (Kantor and Unger 2011). T_{mrt} is therefore influenced by urban geometry and can be used in urban areas to determine areas with low thermal comfort. Mean radiant temperature can be 30°C higher than the air temperature in the same open space. T_{mrt} has also been shown to vary more than air temperature, as the air temperature can differ with just a few degrees from a street canyon and the trunk space beneath a tree (Mayer and Höppe 1987).

T_{mrt} can be used as an indicator for heat related health risks. A study by Thorsson et al. (2014) showed a correlation between mean radiant temperature and increased mortality in Stockholm. Using the same mortality data for Stockholm as the aforementioned study by Rocklov and Forsberg (2008), Thorsson et al. (2014) showed that the correlation between T_{mrt} and increased mortality is stronger than the correlation between mortality rates and air temperature. The study assessed health risks in different age groups and showed that high daily maximum of T_{mrt} increased the mortality rates for individuals in the very old (80+) age group, while high daily minimum values showed a better correlation with mortality rates for ages 45-79. Thorsson et al. (2014) created T_{mrt} thresholds for when the health risks increased for the different age groups. Table 1. shows that risk increases by 5% when the mean radiant temperature is above 55°C for those aged 80+ while T_{mrt} values above 57°C increases the health risks by 5% for all age groups.

Table 1. Risk levels for different age groups in Stockholm (1998-2003) with corresponding T_{mrt} thresholds. Adapted from Thorsson et al. (2014).

	Maximum T_{mrt} thresholds °C		
Risk increase (%)	**All ages**	**Ages 45-79**	**Ages 80+**
0	47.4	46.7	47.6
5	57.1	58.8	55.5
10	-	-	59.4

There are several ways the T_{mrt} can be measured. A globe thermometer is the simplest way to measure but they have a few problems in accuracy compared to the more accurate but also costly way of measuring the fluxes separately (Kantor and Unger 2011), using pyranometers for the shortwave radiation and pyrgeometers for the longwave radiation. The measurements are taken in six different directions: the cardinal directions and radiation from above and below the measurement equipment (Kantor and Unger 2011).

Measuring T_{mrt} can prove to be costly and time consuming. Another method is to simulate T_{mrt} using different software. Some of the more commonly used software packages include RayMan (Matzarakis et al. 2010), SOLWEIG (Lindberg et al. 2008) and ENVI-met (Bruse and Fleer 1998). RayMan computes the mean radiant temperature at a single point while ENVI-met and SOLWEIG can calculate the T_{mrt} for a larger area (Chen et al. 2014). RayMan also has problems to calculate the T_{mrt} in low sun angles but has been shown to otherwise be able to accurately compute the T_{mrt} (Chen et al. 2014). The input data required for ENVI-met includes wind speed and wind direction as well as air temperature and vapour pressure. The computational time for ENVI-met can be quite extensive with many outputs meaning the computational time can be up to several days. SOLWEIG however has less variables and a lower computational time and can be used for citywide analysis (Chen et al. 2014). Because of its capability to compute the mean radiant temperature of a larger spatial area and with reduced computational time the model SOLWEIG has been used in this study.

3.4 Future scenarios

To assess the future change in climate based on human interference the Intergovernmental Panel on Climate Change (IPCC) have developed four different scenarios of greenhouse gas, aerosol and land use development, called representative concentration pathways (RCP), based on their radiative forcing in the year 2100 (Collins et al. 2013). The scenarios are not a prediction of the future nor are they a guideline for what measures should be taken to reduce emissions. They are, however, used in climate models to predict how the climate will change in the future. The RCPs are named after the estimated radiative forcing in 2100 for each scenario e.g. RCP4.5 has a radiative forcing of 4.5W/m^2 while RCP6 have a radiative forcing 6W/m^2. RCP8.5 represents a scenario where little or no mitigation against global warming is taken (Collins et al. 2013). RCP 4.5 represents a future scenario where higher mitigation is taken against greenhouse gas emissions (Collins et al. 2013).

3.5 Study area

Drottninghög is in the northeastern part of Helsingborg (56°3′43″N 12°43′41″E). Originally an orchard the area was converted into a residential area during the 1960s. 1114 apartments were built in what was then Helsingborg’s biggest housing project (Carlsson and Welin 2012). The area is mainly composed of similarly shaped three-story buildings see Figure 2. In between these buildings (Point of interest 4, Table 5) the ground is paved while the areas between these residential houses consist of an open green area with trees in small parks (POI 3). A centrum was built around two small market squares in the south east of the area (POI 8). A large park is located in the upper west of Drottninghög, an area consisting of large trees in the south (POI 2) and a grass covered area in the north (POI 1). Large parking areas are found next to large grocery stores in the western part of Drottninghög. Parking lots are also located in the far south and north of the area with small garages enclosing them.

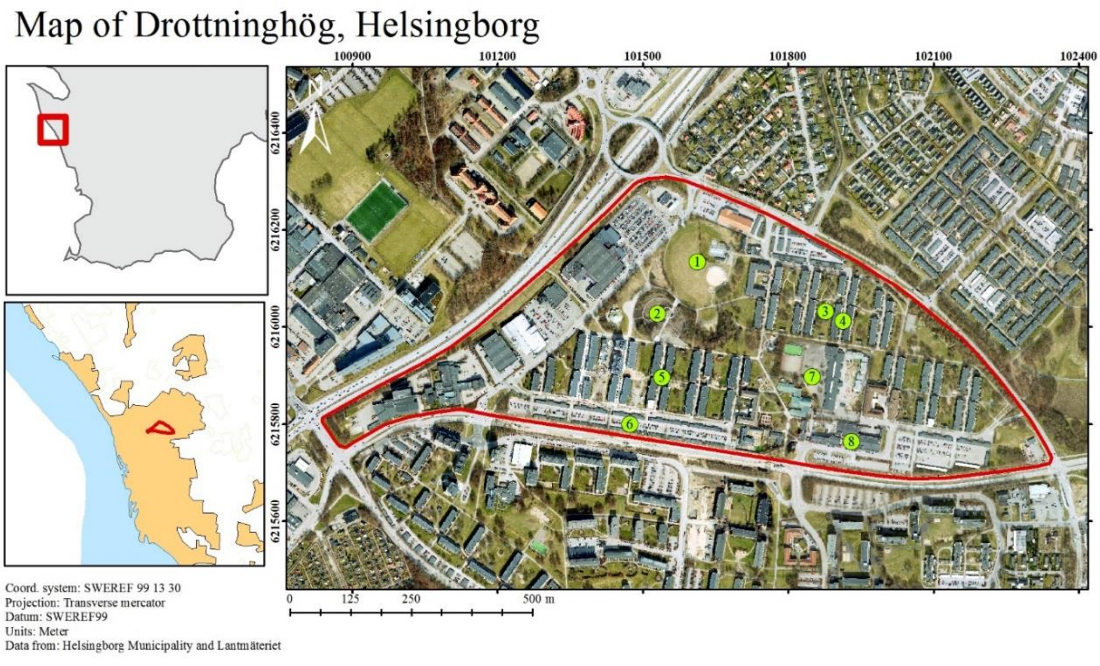

Figure 2. Orthophoto over the study area with points of interest depicted as green dots used for the computation of the number of hours with an increased health risk.

The area is planned to undergo a lot of change with new residential areas being built or being planned to be built in the near future - see Figure 3. Ongoing building projects include two eight-story-high buildings in the northwest area close to the park, an eleven-story office building and a parking house in the southwest, and a new preschool in the northeast. These buildings are replacing areas partly covered by vegetation and grassland. In the parking lots in the south and the area above there are ongoing plans to densify the area with buildings of varying height (Figure 3) (POI 5 and 6). The ongoing plans will create more housing units in Drottninghög, with plans to double the number of apartments in the area (Carlsson and Welin 2012). This will change the urban morphology in a drastic way. Drottninghög, an area that until now has been dominated by 9-meter-high buildings will then have buildings well above it, with the highest planned to be above 45 meters high. The ground cover will also be subject to some change. The parking lots in the south will be replaced by buildings with green areas in between. One of the ambitions with the ongoing plans is to ensure that green areas are promoted within the new residential areas.

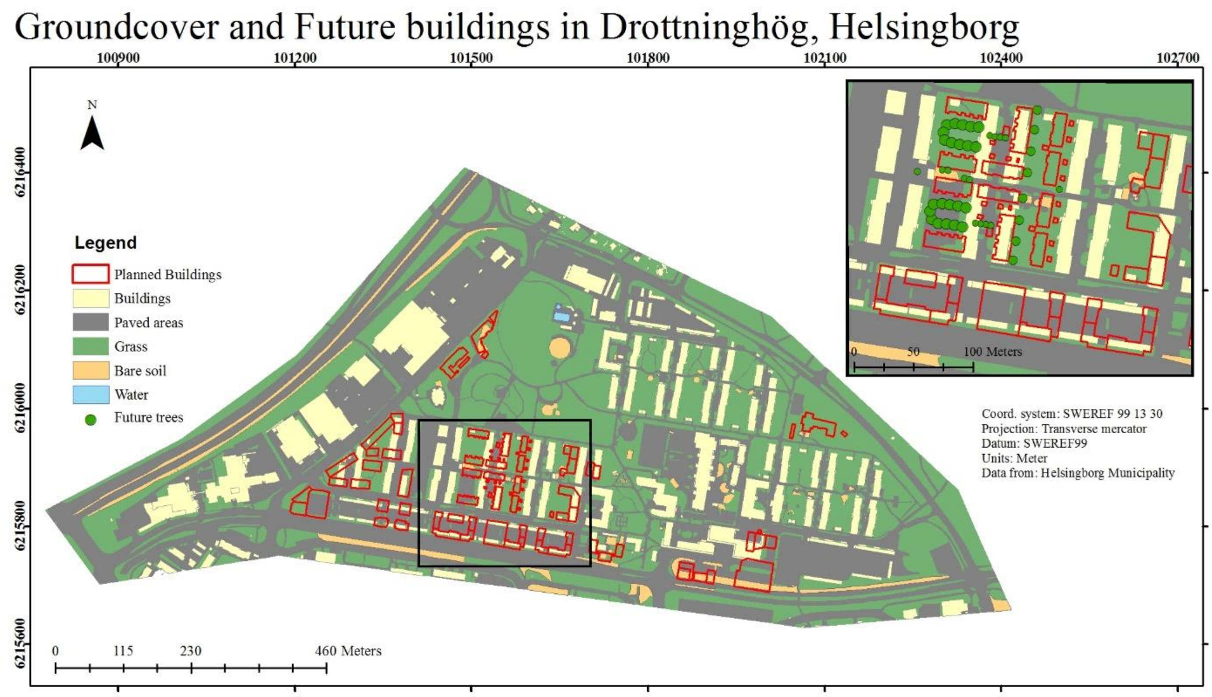

Figure 3. Ground cover map of the study area with future buildings encircled in red. The focus area BoKlok is also depicted, where locations of proposed tree plantations with the future buildings are shown in the upper right.

4 Method

4.1 SOLWEIG

The mean radiant temperature was computed using the Solar and Longwave Environmental Irradiance Geometry Model (SOLWEIG) version 2019a. It was developed by Lindberg et al. (2008) and has been used in similar studies in Sweden (Rödin et al. 2016), Europe (Lau et al. 2015) and Canada (Aminipouri et al. 2019). It is an open source tool incorporated in the Urban Multiscale Environmental Predictor (UMEP) (Lindberg et al. 2018) which is a model accessible as a plugin into the geographical information system software QGIS.

Using air temperature, relative humidity, shortwave radiation and spatial information about the area. SOLWEIG computes the mean radiant temperature (T_{mrt}) from the mean radiant flux density (S_{str}) (Equation 2) which is the sum of all field longwave and shortwave radiation in six directions, together with the absorbance and angular factors of the individual object (Equation 1) (Lindberg and Grimmond 2011).

$$S_{str} = \xi_k \sum_{i=1}^{6} K_i F_i + \varepsilon_p \sum_{i=1}^{6} L_i F_i \quad [\mathrm{W}/m^2] \tag{1}$$

Where the sum over *i* is for six directions, *K* represents the shortwave radiation density, *L* is the Longwave radiation density ξ_k is the absorption coefficient of the shortwave radiation and *F* is the angular factor between a person and the surface. ε_p is the emissivity of the human body.

The absorbance factor for the human considered is 0.7 for shortwave radiation. Angular factors for the incoming radiation from above and below are 0.06 and 0.22 from the cardinal directions. The emissivity of the human body is considered as 0.97 in SOLWEIG (Lindberg et al. 2008).

The incoming shortwave radiation fields are estimated using a function of the diffuse, direct and global radiation as well as view factors. While the incoming longwave fields are estimated using the sky and wall emissivity and view factors. The outgoing longwave radiation is estimated from shadow patterns, air temperature and emissivity of the ground.

From the mean radiant density, the mean radiant temperature is calculated using Stefan Boltzmann's law

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{\varepsilon_p \sigma}} - 273.15 \quad [°\mathrm{C}] \tag{2}$$

Where σ is Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4}) ε_p is the emissivity of the human body and S_{str} is the mean radiant density ($\mathrm{W/m^2}$)

The model uses direct, diffuse and global radiation for the computation. The direct and diffuse parts of the shortwave radiation can be computed inside the model using the global radiation with the use of air temperature and relative humidity (Lindberg and Grimmond 2011). Apart from meteorological input the model uses urban morphology to determine shadow patterns. The model is a 2.5d model as it uses height data as an input to calculate T_{mrt} but the resulting layer is 2d-layer with values represented at a height of 1.1m (Lindberg and Grimmond 2011). The model uses the height of buildings, trees and the trunk height of the trees. This means 3 digital surface models (DSM), which represents the height of objects are needed: a ground and building height DSM, a vegetation canopy DSM and a trunk zone DSM. The trunk zone DSM can be calculated inside the model (Lindberg and Grimmond 2011). Additionally, the model can be used with information about the ground cover to include the effects of different ground cover (Lindberg et al. 2016). Albedo and emissivity values used in SOLWEIG for the different surface types are shown in Table 2.

Table 2. Albedo and emissivity values for different surfaces in the ground cover layer. Values provided within the model SOLWEIG are based on the study by Lindberg et al. (2016)

Surface type	Albedo	Emissivity
Paved areas	0.18	0.95
Water	0.05	0.98
Grass	0.16	0.94
Bare soil	0.25	0.94
Buildings	0.2	0.9

4.2 Spatial data

The ground cover layer was created by digitizing an aerial photograph from 2018 (Table 3) and divided into the five different classes used in SOLWEIG: paved, grass, buildings, water and bare soil. The polygon layer so created was then converted into a 2x2m raster. The vegetation digital surface model was created from a digital surface model from Lantmäteriet collected from 2017. Originally a point cloud layer, with 0.25m distance, the layer was converted into a raster with 2m resolution. The created raster layer included both building and ground heights above mean sea level. The areas occupied by buildings were removed as were heights beneath three meters to only include vegetation with a substantial effect on shade. The same threshold of three meters is used in the model to calculate the wall height (Lindberg et al. 2008). The vegetation DSM was then updated to the aerial photograph as zones of vegetation had been removed between 2017 and 2018. The ground and building DSM and the digital elevation model were obtained from the municipality of Helsingborg. These datasets were provided in a 1x1m resolution see Table 3. To speed up the SOLWEIG processing time these were converted into 2x2m resolution using the mean value of the cells to be aggregated. Since the model requires the same extent and resolution of all input datasets, 2x2m resolution was applied to all layers created.

The municipality also provided information about the future building situation at Drottninghög such as location and height of buildings, changes to ground cover and removal/addition of trees. Using this information, the existing layers were updated. In particular, the ground and building DSM was updated by creating a building layer with height above ground level. This layer was then converted into a raster layer and the heights were added on to the existing DEM. The landcover was updated using an existing polygon layer with the future ground cover provided by Helsingborg municipality. However, this layer did not cover the whole Drottninghög. So, the ground cover was set to have equal amounts of paved and grassland in areas where information was missing, especially around the ongoing constructions. This in order to consider the ambitions of the municipality’s plans for Drottninghög (Carlsson and Welin 2012). The vegetation DSM was updated by removing trees where new buildings would occur and adding trees in the focus area BoKlok (Figure 3). The future tree height and crown diameter was determined by having the crown diameter half of the tree's height. The future trees in the open areas were then given a height of 12m and 6m in crown diameter. Trees near buildings were given a height of 8m and 4m in crown diameter. A middle class was also applied for some of the trees with a height of 10m and crown diameter of 5m.

Table 3. Information about datasets retrieved from Lantmäteriet and Helsingborg municipality

Dataset	Year	Resolution	Source
Ground and building digital surface model	2016	1x1m	Helsingborg municipality
Digital elevation model	2016	1x1m	Helsingborg municipality
Orthophoto	2018	0.08x0.08m	Helsingborg municipality
Surface model from air photo	2017	0.25x0.25m	Lantmäteriet

4.3 Meteorological data

Hourly meteorological data of air-temperature, shortwave radiation and relative humidity was collected from the summer months of June, July and August in 2016 and in 2018. The data was collected from SMHI meteorological stations in Helsingborg and Lund (Table 4), with shortwave radiation collected from Lund in the absence of measured shortwave radiation data in Helsingborg. Hours with missing data were filled using linear interpolation.

Table 4. Information about the SMHI meteorological stations used to collect data for the summer (June-August) 2016 and 2018.

Station id	Parameter	Lat (DD)	Long (DD)	Elevation (m.a.s.l)
62040	Air temperature	56.0304	12.7653	43.0
62040	Relative humidity	56.0304	12.7653	43.0
53445	Shortwave radiation	55.7137	13.2124	85.0

Year 2018 can be regarded as an extremely hot summer (SMHI 2018) while the temperature for Scania in the summer of 2016 was just above the average for the period 1961-1990 (SMHI 2016). To estimate future scenarios for the year 2100 with a warmer climate the average of nine regional climate models for the period 2070-2099 for the area Scania was used to estimate the summer temperature increase. The increase was based on the values for the period 1961-1990 (Ohlsson et al. 2015). Using the air temperature data from the years 2016 and 2018 the temperature was thus increased uniformly for all hours by 2°C for RCP 4.5 and 3.5°C for RCP 8.5 while the relative humidity and shortwave radiation was left unchanged. This resulted in six different meteorological datasets being assessed: a normal summer in the year 2016, two future normal summers by the end of the century with varying temperature increase, an extreme summer in 2018 and lastly two future extreme summers by the end of the century with varying temperature increase.

4.4 Computations

The daytime average of T_{mrt} was computed for the different scenarios to identify areas with high T_{mrt} during the hours when people are outdoors. The six meteorological datasets were used for both the current and future building situation in order to separate the influence of buildings and higher air temperatures. To assess the health risks due to high values of T_{mrt} within Drottninghög the computation of the number of hours using the threshold 57°C determined by Thorsson et al. (2014) (Table 1) was computed using the SOLWEIG analyzer also included in UMEP. The health risk was computed for the points of interest shown in Figure 2, with a description of each point given in Table 5. The values of each raster were extracted for each of the points with a mean value taken from the cell in which the point was located and the neighboring cells.

Table 5. Description and ground cover class of the point of interest (POI) (shown in Figure 2) used to compute the number of hours with a T_{mrt} above 57°C

POI	**Description**	Ground cover
1	Open Grassland	Grass
2	Grassland surrounded by tree	Grass
3	Grassland between buildings	Grass
4	Street canyon 9m high buildings	Paved
5	Street canyon 12m high buildings	Paved
6	Courtyard 20m high buildings	Grass
7	Paved schoolyard	Paved
8	Market square	Paved

To identify the influence of vegetation and new buildings at a smaller scale, a focus area (BoKlok) was selected in the southwest (Figure 3). Here the meteorological dataset was used for a normal summer in 2100 according to RCP8.5 to compute the daytime average for both the current and future building situation with and without vegetation.

5 Results

5.1 Normal summer

For a normal summer, in the current building situation, areas with a high daytime mean T_{mrt} are located at open places, with values approximately 35°C, where the ground cover is paved (Figure 4a). The cooler areas with a T_{mrt} around 20°C are primarily located in tree covered areas. Open grasslands such as the open park in the northwest (Figure 4a) have a T_{mrt} around 30°C. The buildings give some shade on the western side of the buildings leading to values of T_{mrt} being lower compared to the eastern side.

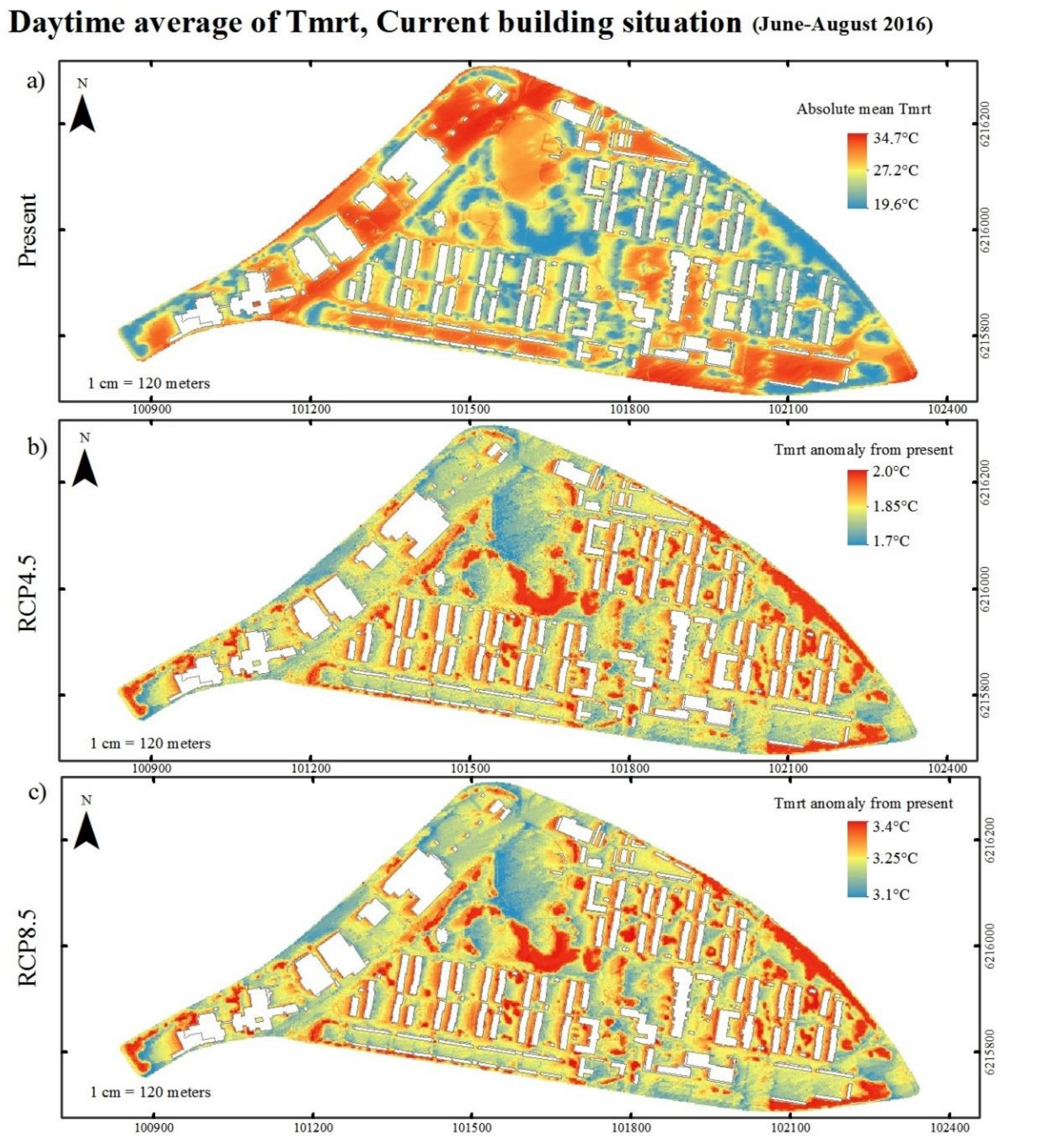

Figure 4. Mean radiant temperature (T_{mrt}) daytime average for the current building situation in Drottninghög for a normal summer (June-August). a) Absolute daytime average for the present (2016), b) T_{mrt} anomaly for a 2°C increase in air temperature RCP4.5 compared to present time (2016), c) T_{mrt} anomaly for a 3.5°C increase in air temperature RCP8.5 compared to present time (2016).

For the warmer scenarios the increase in T_{mrt} follow the same trend for the both scenarios (Figure 4b and 4c). Areas occupied with trees experience the highest increase with a T_{mrt} increase of 2°C in RCP4.5 (Figure 4b). The area on the western side of buildings also sees an increase of around 2°C similar to the increase in air temperature. The open grassland experiences less of an increase with values around 1.7°C. Lower anomaly values are also found in the open paved areas with a temperature increase around 1.9°C. For RCP8.5 the increase is higher than RCP4.5 with trees also experiencing the highest increase in temperature with an increase around 3.4°C (Figure 4c). Areas with shade experience a slightly smaller temperature increase than that of trees with values around 3.3°C. Open areas such as the parking lots and the eastern side of buildings see less of an increase with values around 3.1°C.

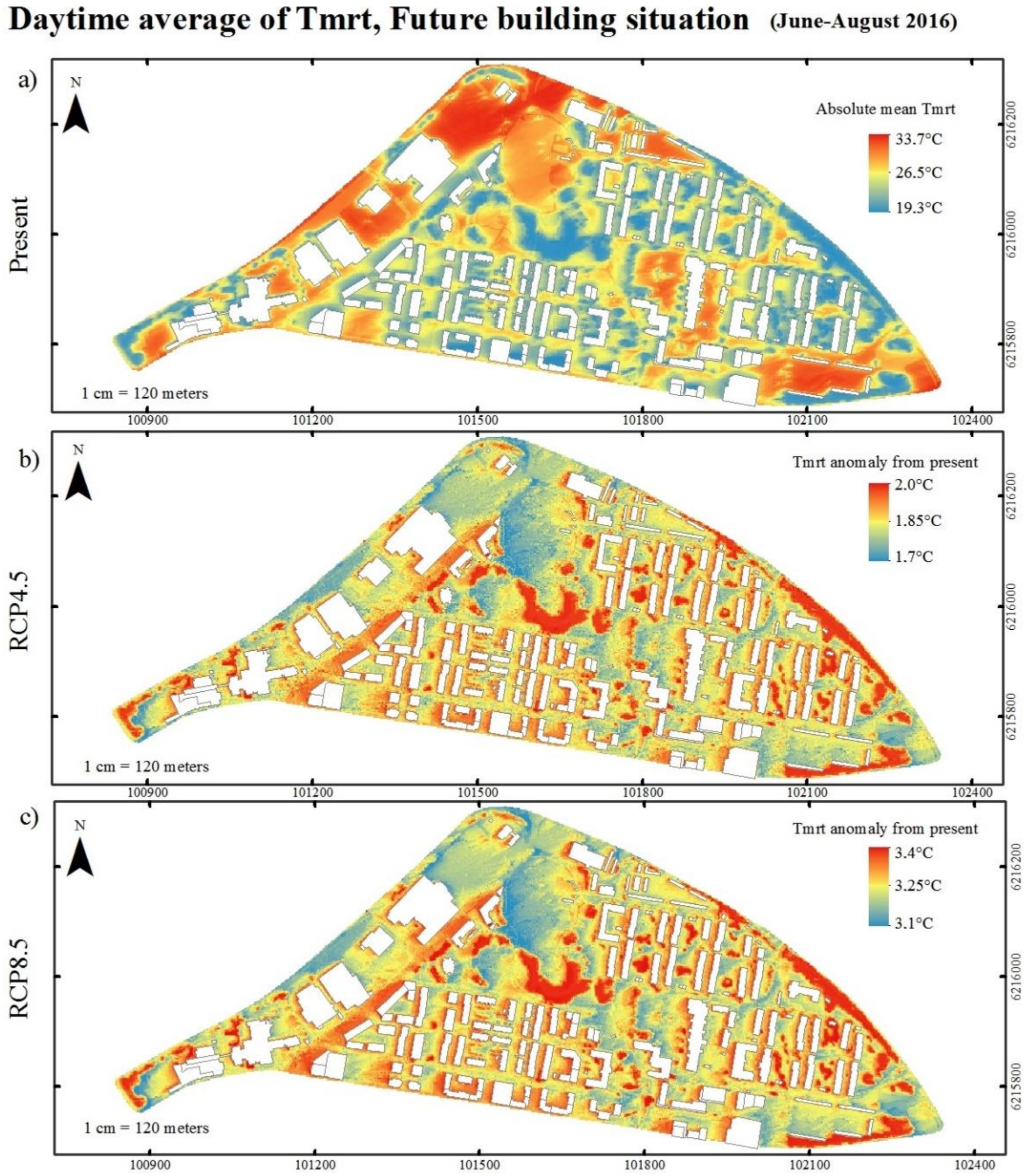

Figure 5. Mean radiant temperature (T_{mrt}) daytime average for the future building situation in Drottninghög for a normal summer (June-August). a) Absolute daytime average for the present (2016), b) T_{mrt} anomaly for a 2°C increase in air temperature RCP4.5 compared to present time (2016)), c) T_{mrt} anomaly for a 3.5°C increase in air temperature RCP8.5 compared to present time (2016).

For the future building situation in a normal summer the highest values of T_{mrt} are found in the parking lots with values around 33.7 °C (Figure 5a). the minimum values are slightly lower than for the current building situation with 0.3 °C. The buildings

constructed on the parking lots in the south are now areas of cooler zones with T_{mrt} in between the buildings around 20°C. The future building situation also create further shade with large zones of lower T_{mrt} along the western side of the buildings.
The increase in future situations follow the same trend as for the current building situation. The areas occupied with trees experience the highest increase in temperature with 2°C (Figure 5b). This is also the case with shaded areas with a T_{mrt} increase of 2°C in RCP4.5 and 3.5 °C in RCP8.5 (Figure 5c).

5.2 Extreme summer

The extreme summer has maximum values approximately 6°C higher than the maximum values of the normal summer - see Figure 4a and 6a. The minimum values are 4°C higher for the daytime average for the summer 2018 than in the summer of 2016. The difference between a cooler area and a warmer area in the extreme summer is therefore increased with a difference of 16°C compared to around 14°C for a normal summer (Figure 4a and 6a).

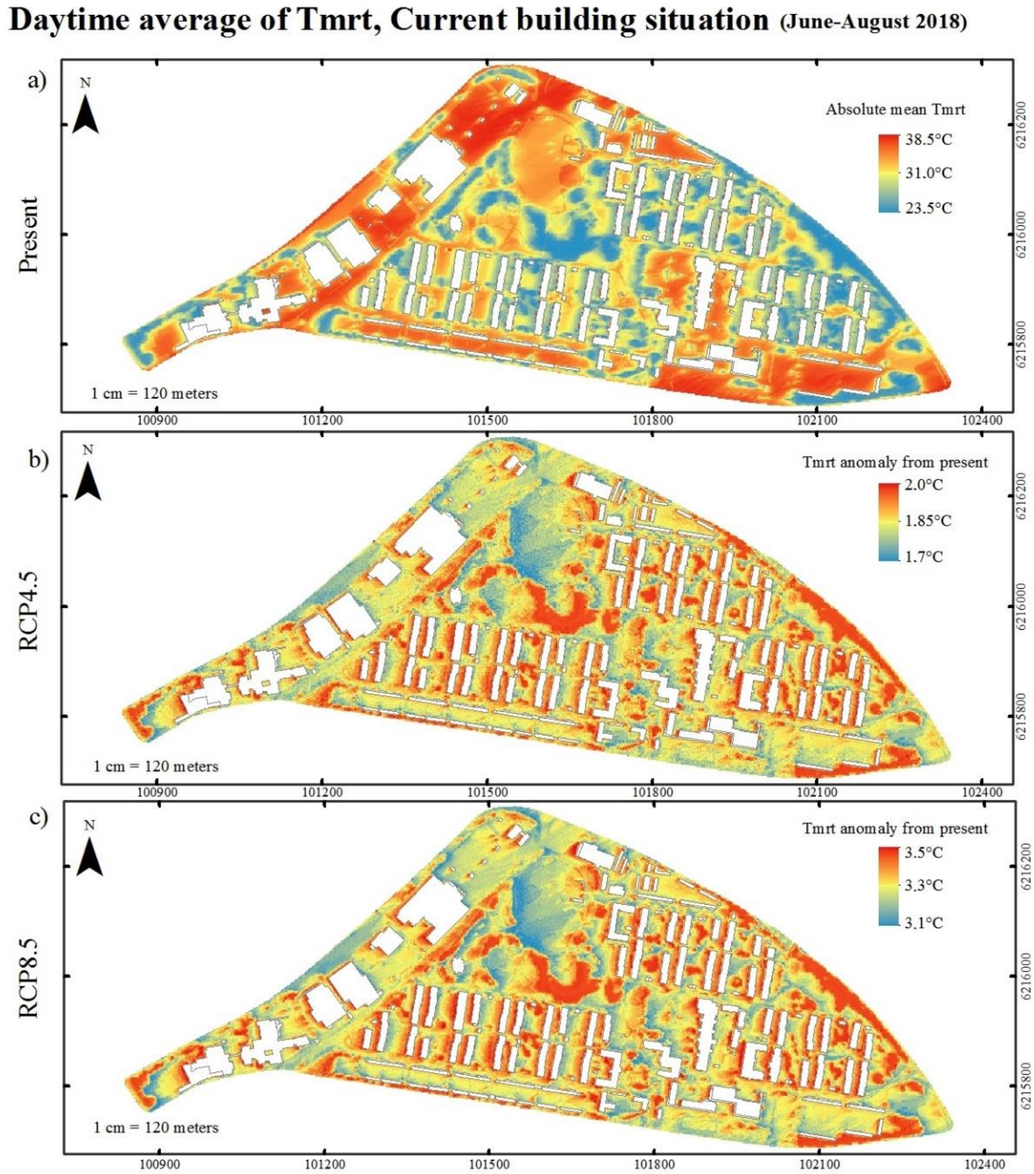

Figure 6. Mean radiant temperature (T_{mrt}) daytime average for a current building situation in Drottninghög for an extreme summer (June-August). a) Absolute daytime average for the present (2018), b) T_{mrt} anomaly for a 2°C increase in air temperature RCP4.5 compared to present time (2018), c) T_{mrt} anomaly for a 3.5°C increase in air temperature RCP8.5 compared to present time (2018),

The absolute mean values of T_{mrt} in an extreme summer in a future building situation have value approximately 39 °C for the open paved areas such as the parking lots. The open grassland has values of T_{mrt} with values approximately 35°C. The shading of the higher buildings constructed in the south create substantial shade with T_{mrt} values in the shaded areas around 23°C with similar values to areas occupied with trees. The open grassland has a T_{mrt} above 31°C, which is slightly less than the paved areas such as the schoolyard and the centrum.

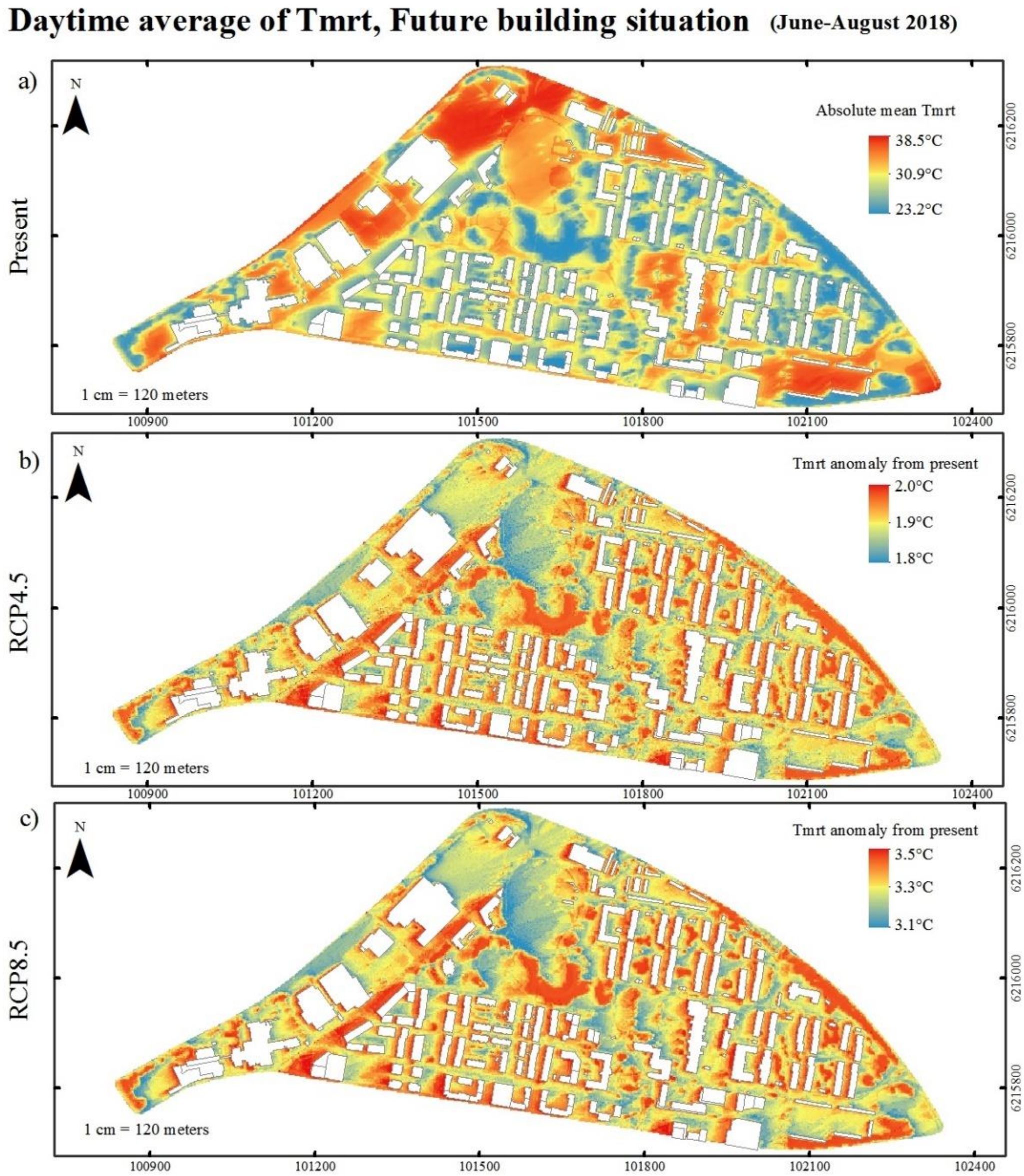

Figure 7. Mean radiant temperature (T_{mrt}) daytime average for a future building situation in Drottninghög for an extreme summer (June-August). a) Absolute daytime average for the present (2018), b) T_{mrt} anomaly for a 2°C increase in air temperature RCP4.5 compared to present time (2018), c) T_{mrt} anomaly for a 3.5°C increase in air temperature RCP8.5 compared to present time (2018),

For the future scenarios with increasing temperatures - see Figure 7b and 7c. The increase in T_{mrt} for the shaded areas is higher than for the trees with shaded areas in the temperature follows the same pattern as Figure 4-6 with the T_{mrt} increase in the range of the increased air temperature.

5.3 Hours with increased mortality risk

The number of hours above 57°C for the points of interest (locations shown in Figure 2) show a clear difference depending on the different warmer scenarios. During a normal summer an open grassland located in the large park shows an increase from 5 hours to 21 in RCP4.5 (Table 6). This increases to 36 hours when the temperature increases by 3.5°C for RCP8.5. This increase pattern is similar for the different grasslands (POI 1-3) where grassland between buildings show a similar pattern but where displaying no hours above 57°C in the present scenario. With increasing future air temperatures, the number of hours increases to 29 for RCP8.5. Grassland surrounded by trees have values in between those of an open grassland and a grassland between buildings. With a grassland surrounded by trees having 3 hours in total in the present scenario which increases to 19 if a 2°C increase is considered and 33 hours in RCP8.5.

The current street canyon, between nine-meter-high buildings, has 33 hours with an increased health risk for all ages in the present normal summer. This increases to 63 hours of increased risk in RCP8.5 by the end of the century. The street canyon between the planned 12-meter-high buildings has 5 more hours of risk in the present scenario compared to the 9-meter-high buildings. The number of hours by the end of the century according to RCP8.5 is 76 hours. The planned courtyard heavily surrounded by 20-meter-high buildings near the parking lots have only 8 hours in total for a whole summer and increases to just 14 hours in a RCP8.5 in the end of the century. The paved schoolyard has the most hours of increased health risk with 48 hours which increases to 75 hours in RCP4.5 and 102 hours in RCP8.5. The market square partly surrounded by buildings (Figure 2) has fewer riskier hours than the street canyons and increases to 32 hours in RCP4.5 and 37 hours in RCP8.5.

*Table 6. Number of hours with T_{mrt} above 57°C for point of interests for a normal (2016) and an extreme (2018) summer (June-August). For each summer type different scenarios are represented, future RCP scenarios at the end of the century (2070-2099) and the present situation in Drottninghög, Helsingborg (2018). * Future building situation.*

	Normal			**Extreme**		
	Present	***RCP4.5***	***RCP8.5***	***Present***	***RCP4.5***	***RCP8.5***
1. Grassland	5	21	36	16	46	98
2. Grassland surrounded by trees	3	19	33	17	45	94
3. Grassland between buildings	0	16	29	13	44	80
4. Street canyon 9m high buildings	33	49	63	104	137	179
5. Street canyon 12m high buildings*	38	57	76	127	183	236
6. Courtyard 20m high buildings*	8	13	14	26	43	48
7. Paved Schoolyard	48	75	102	160	232	286
8. Market square	16	32	37	44	91	135

For an extreme summer the number of hours with a T_{mrt} above 57°C is substantially higher than the present normal summer (Table 6). The figure has trebled for almost all points of interest. The number of hours for the grassland increases to 46 hours when the temperature increases by 2°C at the end of the century (RCP4.5). When the temperature increases by 3.5 °C in RCP8.5 the number of hours with an increased risk

for all ages increases to 98 hours. The grassland in more shaded areas (POI 2-3) have almost the same number of hours in RCP4.5 with 45 respective 44 hours but in RCP8.5 the grassland between buildings have 14 less hours of T_{mrt} above 57°C. All of the grassland points have less risk hours in a present extreme summer than a normal summer in a 3.5 °C warmer scenario. This is not the case for the rest of the points of interest for the 9-meter street canyon where the number of hours in the present scenario is 104 hours compared to 63 in RCP8.5 for a normal summer. This value increases in RCP4.5 by 33 hours and reaches 179 in RCP8.5. The street canyon surrounded by 12-meter-high buildings have 23 more risk hours than that of the nine-meter-high buildings in the present extreme summer. The difference between the current street canyon and the one planned in BoKlok increases with the different future scenarios. In RCP4.5 the difference is 46 hours and 57 hours in the RCP8.5 scenario by the end of the century. For the courtyard the number of hours is substantially higher for the extreme summer in the present scenario compared to the normal summer. The hours in the extreme summer increases to 43 hours in RCP4.5 with values similar to those of the grassland. In RCP8.5 however the number of hours increases just slightly compared to for example the grasslands with the courtyard having 48 hours in RCP8.5.
The paved schoolyard has the most hours in the present scenario for an extreme summer with 160 hours of increased risk for all ages. The Figure rises to 286 hours in the RCP8.5 scenario. The market square has 44 hours in the present scenario, a number that is almost doubled in the RCP4.5 scenario and increases to 135 in a 3.5 °C warmer scenario. In general, we find that there is an overall increase in risk hours above 57°C with an increasing air temperature scenario. However, the effect is greater for paved areas than for grasslands, and open areas are more susceptible to high T_{mrt} values.

5.4 Effect of trees

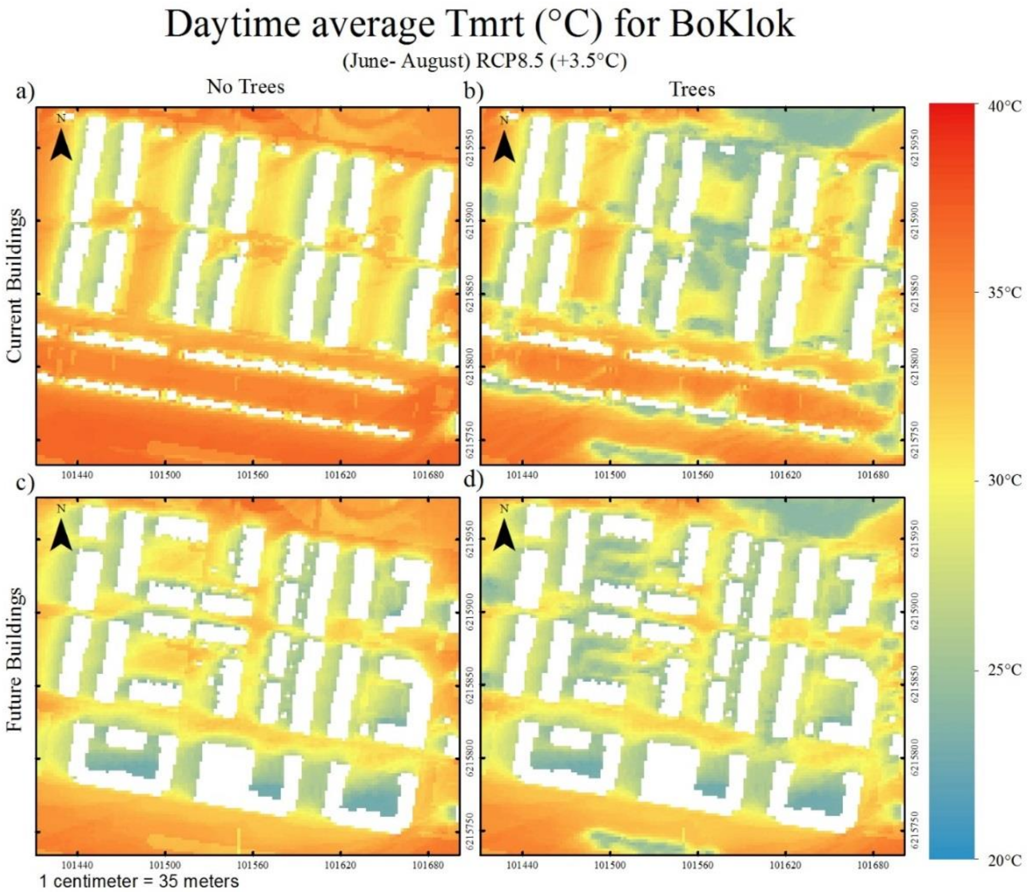

Figure 8. Daytime average T_{mrt} (°C) in the focus area in Drottninghög for a normal summer (June-August 2016) in a future scenario according RCP8.5 (+3.5°C): a) Current building situation without trees, b) Current building situation with trees, c) Future building without trees, d) Future building situation with trees.

The difference in T_{mrt} for the different scenarios can clearly be seen in the zoomed in map of the study area in the southwestern part of Dottninghög (BoKlok) (Figure 8a,8c). The parking lots in the current building situation are areas of higher T_{mrt} and display a daytime average for the summer above 35°C. In the future building situation with buildings above 20m the area is cooler with T_{mrt} below 20°C (Figure 8c). Among the residential houses the temperature in the current building situation (Figure 8a) is > 30°C with cooler areas < 25°C near the buildings. In the future building situation the residential area will have a mean radiant temperature of apporoximately 30°C with T_{mrt} below 25°C near buildings.

The inclusion of trees in the current building situation create zones with mean radiant temperature around 20°C (Figure 8b), with no trees the T_{mrt} is modelled to be over 10°C higher (Figure 8a). The trees also decreases the T_{mrt} in the future building situation (Figure 8d). The trend is similar with change in the open areas between buildings now occupied by trees experiencing a daytime mean of around 25°C instead of above 30°C. The trees planted close to the buildings on the eastern side (Figure 3) result in no greater difference in the daytime average.

6 Discussion

Measuring the outdoor thermal comfort in high-latitude regions which may not have experienced extreme heats in the past is an important consideration for the future planning of urban areas. Studies have shown that inhabitants in these regions have less of a resilience towards extreme heat (Kalkstein and Davis 1989; Oudin Åström et al. 2018). The increasing urbanization could lead to a further densification of the urban areas showcasing the importance of including future building plans in simulation of future scenarios. The result can in that case help municipalities and decision makers to plan areas to improve the thermal comfort of its citizens. Implementing the right measures to counteract the increased temperatures in cities could lead to reduction in the use of air-conditioning to cool houses. Air-condition not only increases the electricity use in cities but also increases the outdoor temperature (Chen et al. 2009). Heat waves are predicted to be more frequent in the future and especially in the urban areas (Hoegh-Guldberg et al. 2018). The increased number of heat waves will affect the urban populations more than the rural with increased mortality levels in the city (Tan et al. 2010). This justifies the need to study the spatial variability of thermal comfort in a city to be able to mitigate zones of extreme heat through prudent city planning.

6.1 Difference between current and future building situation

The Future building plans for Drottninghög will create more shade in certain areas, as the constructed buildings will be significantly higher, the shade behind these buildings have lower T_{mrt} than surrounding values (See Figure 5a and 7a). The building plans will also remove areas with high values of daytime T_{mrt} such as the parking lots in the current building situation. The construction of these high buildings will cause less shortwave radiation to reach the ground in certain areas. This seems to counterbalance the effect of more intercepted outgoing longwave radiation. The difference can also be seen in the BoKlok area where the new construction will also mean a small reduction in between the areas of the formerly nine-meter-high buildings (Figure 9). Considering an extreme summer in comparison to a normal summer the result is striking where an extreme summer can have a daytime average T_{mrt} 6°C higher than a normal summer seemingly regardless of the building situation with temperatures in the same range for both building situations.

The difference can be clearly seen if the temperature increases by 2°C or 3.5°C. The temperature increase seems to be in the range of the scenarios' air temperature increase. However, some spatial variation can be seen in the study area (Figure 4b-7b). Shaded areas experience a higher temperature increase. Whether this is due to SOLWEIG setting the surface temperature in shaded areas to be equal to the air temperature, and not as a result of the incoming shortwave radiation as for the open areas, when calculating the outgoing longwave radiation (Lindberg et al. 2008) cannot be determined in this study. This report is not intended to be an evaluation of the model to correctly predict the T_{mrt} increase for shaded and open areas when only the air temperature increases. However, in open areas some variation can be seen within the open park as well as the parking lots. The response of different materials to an increased air temperature in relation to radiation fluxes would be interesting to study as it could potentially further highlight the importance of ground cover in relation to thermal comfort for humans.

The future building situation can lower the T_{mrt} in open areas since the buildings replace open areas which have shown to generally have higher temperatures than areas with a lower sky view factor (Chen et al. 2012). The result in this study implies that the shade patterns of the planned constructions in Drottninghög can have a substantial effect on the outdoor thermal comfort. This means further plans in the area or similar building plans need to consider the effect of shade but also the orientation of the buildings. Since this also has a significant impact on thermal comfort. Some street canyons in BoKlok have a higher number of risk hours compared to the existing nine-meter-high building's street canyon (Table 6). The nine-meter-high building's street canyon is in a north to south direction whereas the street canyon studied in BoKlok is in east to west direction. This agrees with the study by Andreou (2013) which also found that the direction east to west experiences higher temperatures than north to south. This is presumably due to shade patterns where east to west street canyons experience more incoming solar radiation than north to south facing ones.

Even though increased shade during the summer can improve the outdoor thermal comfort in the summer the effects of the shade for different seasons must be considered. Less incoming shortwave radiation during wintertime can lead to lower T_{mrt} in the areas shaded by buildings, which could have the reverse effect on thermal comfort, especially for regions experiencing cold winters. Further impacts of more densely built areas have not been dealt with in this study such as changes to wind patterns potentially leading to less advection of heat and removal of air pollutants. Less advection of wind could potentially increase the health risk for humans but also increase the amount of absorbed longwave radiation, by the increased number of pollutants in the air (Roth 2012), increasing the radiation received by the pedestrians.

6.2 Mortality risk in warmer scenarios

The computation of the number of hours above 57°C give a better indication of difference in health risk than the daytime average. When looking at the number of risk hours the difference between areas with different ground cover can more clearly be seen. Areas covered by grass have less risk hours in all scenarios compared to paved areas (Table 6). The difference can also be seen between open areas and areas with less openness to the sky, such as the courtyard having low values compared to the more open areas such as the grassland. The difference in between the street canyons can be attributed to the difference in direction of the street canyons. As mentioned above, with east to west street canyons being more exposed to solar radiation. The difference between the extreme and normal scenario is trebled in number of risk hours with an increased mortality risk for almost all points of interest in an extreme summer (Table 6). An extreme summer in the future can mean a substantial health risk if the temperature increases with 3.5°C with paved areas such as the schoolyard and market square being particularly risky areas. Areas such as the courtyard have less of an increase in risk hours compared to more open areas. As seen in Figure 4b and 4c, T_{mrt} increases slightly more in shaded areas than open areas but the initial daytime average T_{mrt} are lower in areas with substantial shade (Figure 4a). The lower T_{mrt} values seem to only cause a small increase in risk hours for both a normal and extreme summer in 3.5 °C warmer scenario for areas heavily shaded such as the courtyard (Table 6). This suggests that heavily shaded areas remain a place of high thermal comfort even with increasing air temperatures.

The number of hours is higher than in a similar study by Rödin et al. (2016) for the more northern city of Eskilstuna in Sweden but the increase in the future seen here is similar to the study performed in three cities in Europe by Lau et al. (2015) but both studies showed an increase in number of T_{mrt} for open areas and less of an increase in a heavily shaded area. Lau et al. (2015) suggested that narrow street canyons, similar to the courtyard in this study, are less affected by increasing temperature in terms of increased heat related health risks. Assessing the result of increased health risk did not include the proposed inherent resilience to extreme heat in different regions (Kalkstein and Davis 1989; Le Tertre et al. 2006). Without doing a similar study as Thorsson et al. (2014) comparing the mortality rates with high values of Tmrt in Helsingborg or southern Sweden this would be difficult to account for. However, the result can give an indication of the health risk of some of the areas where citizens may spend most of their time outdoors.

6.3 Planting trees as a mitigation strategy

The effect of trees is clearly illustrated in Figure 8a-d. Areas with trees have 10°C lower T_{mrt} than those without. The effect of trees can also be seen all over the area in (Figures 4a-7a), where the cooler areas are located where trees are present. The well-known contribution of trees and vegetation to thermal comfort are the increased latent heat flux as well as the shading of surfaces, and similar studies, also using the model SOLWEIG, have shown that added trees could reduce the impact of an increase in temperature for a future scenario according to RCP4.5 (Aminipouri et al. 2019). The placement of the trees needs to be considered as the shade patterns are important for the radiation fluxes. Planting trees in open areas could reduce the T_{mrt} to a bigger extent than planting them closely to a building on the sunlit walls. The problem with shade in winter needs less consideration regarding trees, as long as the trees planted shed their leaves in winter. Adding trees in areas where the thermal comfort is low can be a suitable mitigation strategy. Other mitigation strategies are discussed in Lai et al. (2019) where changing the urban geometry seems to have the greatest effect. Changing the building materials so less radiation is absorbed is a good measure to lower the surface temperature, but it can also increase the reflected radiation (Chatzidimitriou and Yannas 2015), thus worsening the thermal comfort of the pedestrians. Implementing appropriate urban geometry plans in terms of outdoor thermal comfort is the primary strategy to avoid hot spots in an area. But as constructed buildings may sometimes be limited to change, the planting of trees in an area may be a more accessible and cheaper option to reduce hotspots in the city.

6.4 Sources of error

The model results are based on meteorological measurements of air temperature and humidity outside the city of Helsingborg. Measurements taken outside the city could potentially mean that this study underestimates the T_{mrt} in Drottninghög, as the air temperature within the city could be higher due to the urban heat island effect (Oke et al. 2017). To account for the urban heat island effect or measuring the air temperature within the city could improve the estimation of T_{mrt} by reducing the underestimation that comes with ignoring the urban heat island effect. Additionally, the use of shortwave radiation from Lund is another source of error. Cloud patterns could differ between Lund and Helsingborg, altering the incoming shortwave radiation. Measuring the shortwave radiation within the city, and additionally the diffuse and direct components, could also increase the accuracy of the model result (Lindberg et al. 2008). The assumption of increasing the temperature uniformly is another source of error as only a yearly variation is taken into account in this study. Assuming the humidity and shortwave radiation will be the same in the future is another uncertainty of this study. These variables are also likely to change in the future. Future changes in solar radiation and air temperature have in similar studies been estimated using a statistical downscaling method to compute variation at an hourly scale (Lau et al. 2015; Aminipouri et al. 2019). This could improve estimations of the future scenarios by accounting for daily and hourly variation in future scenarios instead of a yearly average for the summer months.

The proposed building plans analyzed in this report have been retrieved from the municipality of Helsingborg, but the area is still being planned, with areas earmarked for further construction. The area is likely to undergo further change before the end of the century which is the time used for the future scenarios. This could mean the outdoor thermal comfort can change even more in the area. Measuring the outdoor thermal comfort when the future building plans for the area have been finalized could be an interesting aspect to see the result of the mitigation taken. However, the importance of measuring the thermal comfort before construction is essential as the plans can be modified to include measures to mitigate possible zones of low thermal comfort. One aspect not considered in this report, as SOLWEIG uses a general value for albedo and emissivity for buildings, is accounting for the variability of albedo and emissivity of different building materials. This could potentially show a greater difference between the old buildings built in the 1960's and the future buildings.

6.5 Future studies

For future studies the inclusion of wind patterns in Drottninghög to determine zones with deaccelerated wind or acceleration caused by channeling winds should be considered, this could mean that cooling of wind could be considered in calculations of the thermal comfort of humans. It could also further analyze the importance of direction and height of buildings. Further on, considering the effects of humidity on thermal comfort is another aspect that has not been dealt with in this report. By calculating PET, both wind and humidity can be considered. However, in SOLWEIG this is only possible to calculate at certain points using standard values for wind and not over a larger spatial area.

A single hour of extreme heat to the level that it increases the health risk is interesting to compute but a sole hour could have less impact on thermal comfort than consecutive hours of extreme heat. Therefore, it would be interesting to compute the number of consecutive hours of high values of T_{mrt}. The difference in temperature between a rural an urban area is greatest at night (Figure1) (Oke et al. 2017). It would therefore be interesting, for future studies of human thermal comfort in cities, to include relief at night by measuring the T_{mrt} indoors. Because of time constraints this have not been done in this study. It would give a clearer result of how high the health risk is in Drottninghög, especially at night which is believed to be a major cause of increased mortality in urban areas (Tan et al. 2010).

7 Conclusions

- The future building situation in Drottninghög will create areas with lower T_{mrt} by creating shade as well as replace existing parking lots. An extreme summer will have T_{mrt} approximately 6°C higher than a normal summer. The future increase in temperature follows the same pattern regardless of the building situation. The T_{mrt} in future scenarios will closely follow the increase in air temperature for RCP4.5 and RCP8.5.
- The heat related health risk increases drastically with future scenarios with amount of risk hours trebled in a 3.5°C warmer climate. Open areas receiving more solar radiation are more affected in an extreme summer, with the paved schoolyard having 286 hours of increased health risk for all ages. In general, all areas experience an increase in risk hours in a warmer climate. However, grasslands and areas in shade experience less risk hours than open paved areas, with the courtyard experiencing a low increase in comparison.
- Apart from changing the urban geometry of an area the planting of trees is an appropriate mitigation strategy as areas can have a daytime average of 10°C lower T_{mrt} if occupied with trees. The effect of trees is greater in open areas, indicating that the location is important to consider in mitigation strategies.
- For future studies the inclusion of wind patterns is an important aspect to consider as it would improve the evaluation of the effect of the tall and densely constructed building in Drottninghög. It is also an important variable in the thermal comfort of humans, and can be used to compute PET. Measuring indoor thermal comfort at night is another aspect to consider in future studies, to include the heat stress during night when the canopy heat island is at its greatest.

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