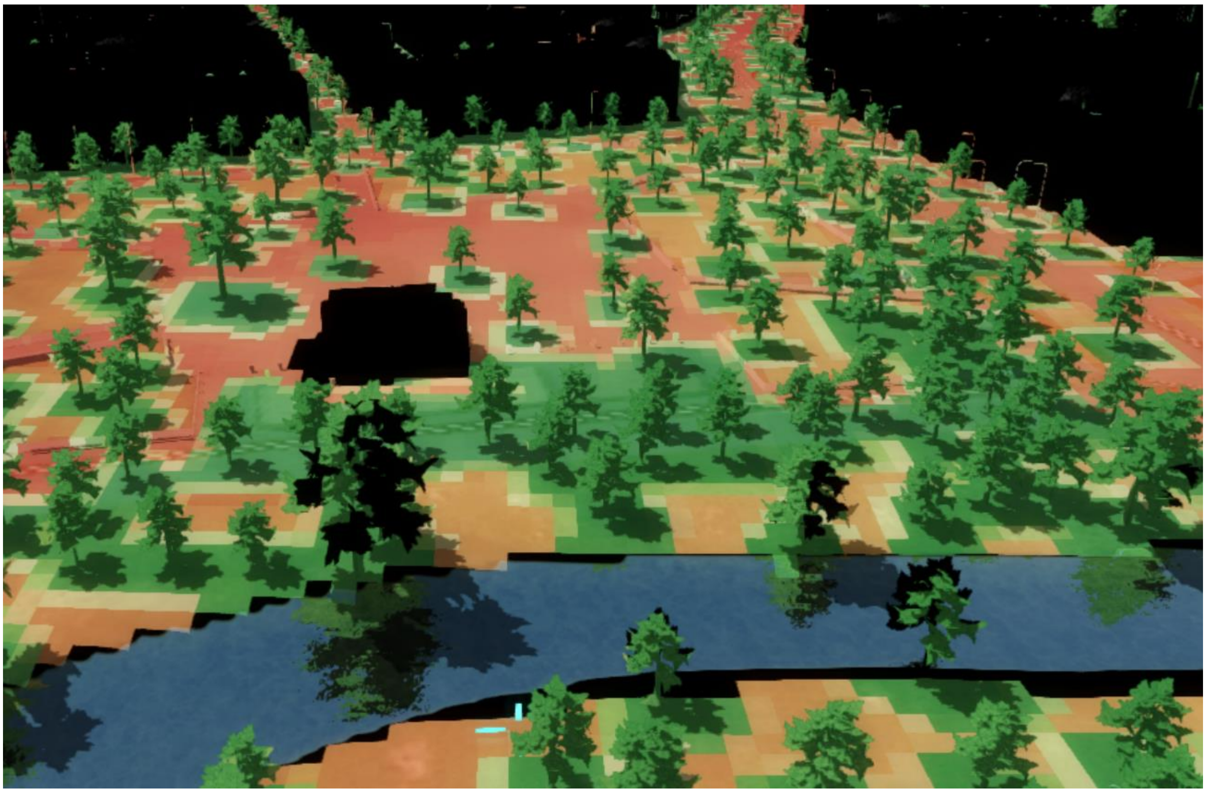

The effect of increasing vegetation cover on heat stress in urban areas affected by global warming: A case study of Rotterdam, the Netherlands

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Abstract

This study assesses how current and future urban heat stress in the Netherlands can possibly be reduced by increasing the vegetation cover. Climate change is expected to increase the global atmospheric temperature, causing the probability of being exposed to heat stress to increase (McCarthy et al., 2010). In urban areas, factors such as the urban heat island (UHI) cause unfavourable conditions for the energy balance of the human body, which leads to the occurrence of heat stress (Oleson et al., 2015). Increasing the vegetation cover is believed to reduce heat stress in the public outdoor space (Lindberg et al., 2016). The aim of this study is to quantify the effect of vegetation on heat stress in urban areas of the Netherlands, in the current and future climate. By doing this, knowledge is gained of how climate change will influence heat stress in urban regions of the Netherlands, and how heat stress can be reduced by increasing the vegetation. The study aims to assess how increasing the vegetation cover affects heat stress in urban areas, by analysing various factors that influence heat stress and the effect vegetation has on these factors. Furthermore, an empirical regression model is used to calculate the physiological equivalent temperature (PET) in Rotterdam, the Netherlands, under current and future climatic conditions. Multiple numerical simulations are carried out for different tree-scenarios involving varying numbers of trees in the study area to determine the heat stress in Rotterdam. The results of the literature study show that vegetation can considerably reduce heat stress by affecting shade and evapotranspiration rates, but its impact on wind can also slightly increase heat stress. Earlier research states that the type and arrangement of vegetation in an area have a strong impact on how effectively vegetation can lessen heat stress (Dimoudi & Nikolopoulou, 2003). The results of the model runs reveal that Rotterdam currently experiences strong to extreme heat stress on summer days with a moderately high probability of occurrence. In addition, heat stress is expected to worsen and become more widespread over time. By 2050, on summer days that occur every 3 years, extreme heat stress is expected in the majority of Rotterdam. In 2085, extreme levels of heat stress can be found over the entire study area. In both the current and future climate, the potential heat stress is not equal throughout the study area, as heat stress is more severe in densely built-up areas in the city centre compared to the surrounding suburbs. On average, the level of heat stress increases when an individual leaves a building. Trees have the potential to decrease the potential exposure of citizens to severe levels of physiological stress during warm summer days. However, increasing the number of trees with 50 percent of the original number of trees will not be enough to lower the average level of heat stress in Rotterdam from ‘extreme’ to ‘strong’ or ‘moderate’ heat stress. Increasing the vegetation cover can be used as a measure to mitigate heat stress in urban areas in the Netherlands, however reducing the inevitable future heat stress caused by climate change will require more than this single mitigation strategy.

Key words: *heat stress, heat mitigation, physiological equivalent temperature (PET), urban planning strategies, urban vegetation, Tygron Geodesign Platform*

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Definition
UHI	Urban heat island
PET	Physiological equivalent temperature
RP	Return period

1 Introduction

Climate change is expected to have substantial consequences for societies, in terms of causing discomfort due to changing precipitation patterns and rising temperatures. Especially rising temperatures are bound to affect societies (Koopmans et al., 2018). Heat stress can occur in extremely hot conditions when a human being is not able to release the heat, and the body's core temperature starts to rise (Kovats & Hajat, 2008). Due to global warming, heat stress is expected to increase in frequency and intensity in the coming years (de Nijs et al., 2019). This will lead to adverse effects on human health (de Nijs et al., 2019). When humans are exposed to too much heat stress for longer periods of time, immense health implications can be a consequence. Weather related mortality, morbidity, and reduced labour productivity are projected to worsen over time (Kovats & Hajat, 2008). Most studies on climate change focus on rural areas rather than urban areas (Hunt & Watkiss, 2011). However, the largest part of the Dutch population lives in urban areas, forty percent of which resides in the Randstad, a coastal agglomeration of the Netherlands' largest cities (Centraal Bureau voor de Statistiek, 2022). The population density in the Randstad area is far greater than in other parts of the Netherlands (Koopmans et al., 2018). Cities in the densely populated coastal region of the Netherlands, such as Rotterdam, increasingly experience heat stress (Koopmans et al., 2018).

Studying the effects of global warming on urban climates differs a lot from studies carried out in rural areas, because the urban environment generally has a higher temperature than its rural surroundings (Yang et al., 2016). The first observations that suggested that the urban climate is different from the rural climate, were carried out by Luke Howard in 1833 (Howard, 1833). He discovered that temperatures in the urban area of London were considerably higher than in the surrounding countryside. Ever since, the effect of urbanization on local climates has been a globally recognized phenomenon that has adverse consequences for human health. This rise of temperature is caused by a phenomenon called the urban heat island (UHI) (Stewart, 2011). The UHI is defined as the difference in air temperature between an urban area and its surrounding rural area (Yang et al., 2016). The phenomenon is the consequence of heat accumulation, which is mainly caused by activities of human beings and urban constructions.

When a human being is exposed to heat for long periods of time nuisance occurs, which can range from minor discomfort such as lack of sleep (Santamouris, 2020), to death in extreme cases. Such extreme cases can occur when during longer periods of extreme heat, such as heat waves, the human body is exposed to the high temperatures for long periods of time. Deaths occur more during heat because long exposure to heat causes malfunctioning of the body. Vulnerable demographic groups such as elderly or ill people are most at risk for this effect of heat stress. In the Netherlands the number of excess deaths related to heat stress in the year 2003 is expected to have been somewhere between 1400 and 2200 (Garssen et al., 2005). Climate change will increase the frequency, duration and intensity of heat waves in the Netherlands, which will increase heat stress in densely populated areas drastically (Koopmans et al., 2018).

Near-coastal urban areas are the most densely inhabited and economically productive areas in the world (Tamura et al., 2019). Previous studies have shown that near-coastal cities in maritime climates have a large probability of experiencing severe heat stress (Molenaar et al., 2016). This includes Rotterdam, the Netherlands, where the temperature of the UHI in the urban area is up to seven ℃ higher compared to the rural surroundings during hot days (Heusinkveld et al., 2014). Heat stress is expected to increase considerably in this area from the early 2020's, especially in the hottest climate scenario from the Royal Netherlands Meteorological Institute (Koopmans et al., 2018). The UHI is influenced by multiple environmental factors, and a better understanding of these factors will contribute to better mitigation strategies for reducing heat stress.

Identification of the health risks of the exposure to heat is recommended by the National Institute for Public Health and the Environment (RIVM) of the Netherlands (de Nijs et al., 2019). Exposure to heat stress is analysed by using the physiological equivalent temperature. The physiological equivalent temperature (PET) is air temperature as perceived by a human being (Höppe, Peter, 1999). The value of the PET depends on environmental and meteorological factors, such as regular air temperature measurements, but also on conditions of the human body and factors that determine the exposure (Matzarakis et al., 1999). For example, during a very hot day, the air temperature can be measured at 25 ℃, however in direct sunlight a PET can be experienced of 40 ℃ If the PET is relatively high, heat stress can be experienced. If the PET is relatively low, then there is cold stress, which can also lead to negative health impacts. The assessment of heat stress in this study is carried out with the use of PET, because air temperature alone is not enough to give an indication of the actual thermal discomfort that is experienced at a certain location.

There are multiple factors that influence the temperature in an urban area. The two main influencing factors of heat in the urban environment are the occurrence of constructions and vegetation. Quantifying the effect of vegetation on urban heat stress can be very interesting because modifying the occurrence of vegetation in an urban environment is financially viable and requires little effort compared to the modification of concrete structures (Steeneveld et al., 2011). Because the presence of vegetation influences the outdoor temperature and its occurrence is easy to modify in urban areas, vegetation cover adaptation is a relevant scenario for mitigating heat stress (Giridharan et al., 2008).

Vegetation has a considerable effect on the PET due to different processes that influence the microclimate (Huang et al., 1987). Climate and vegetation are strongly connected to each other, due to the fact that climate often determines vegetation types and characteristics on a certain location (Ren et al., 2022). More relevant for this study, is that temperatures can be influenced by vegetation on a local scale (Salmond et al., 2016).The presence of vegetation has a negative as well as a positive influence on the PET. This is because the presence of vegetation influences processes such as evapotranspiration, shading and wind blockages (Chen, D., Wang, Thatcher, Barnett, Kachenko, & Prince, 2014). These processes all influence the energy balance in a city, which affects the air temperature. Urban vegetation has the ability to mitigate heat stress, however its influence must be studied carefully to prevent adverse effects, such as wind blockages, from happening. Quantification of the effect of vegetation on heat stress in urban areas for current and future climates is required in order to propose measures to prevent societies from being exposed to unhealthy amounts of heat stress (De Nijs et al., 2019).

The aim of this study is to quantify the effect of vegetation on heat stress in current and future climates in urban areas of the Netherlands. By doing this, knowledge is gained of how climate change will influence heat stress in urban regions of the Netherlands, and how this heat stress can be changed by modifying the vegetation. Dutch policy makers aim to mitigate the effect of climate change on heat stress in current and future climates. To substantiate a comprehensive understanding of the effect of vegetation on heat stress, heat stress in the Dutch city of Rotterdam is simulated with the use of a model. The vegetation scenario of Rotterdam will be modified in the simulation, to quantify the effect of the presence of vegetation on heat stress in the current and future climate. To understand the effect vegetation has on heat stress, a better understanding of the different feedback mechanisms between vegetation and PET is required. Especially for city planning purposes, there is a need for knowledge of processes that can reduce heat stress. This is necessary to minimize the impact of global warming on heat stress related problems in urban areas.

Due to limitations in time of this study, it is not possible to simulate all urban areas of the Netherlands. Therefore, a limited research area was chosen. The study area of this thesis is the urban agglomeration of Rotterdam, the Netherlands. Rotterdam was chosen as research area because its spatial characteristics make it a fitting location to act as reference for the large urban area in the Netherlands. Also, Rotterdam is located in the most densely populated part of the Netherlands, the Randstad. Because Rotterdam aims to be climate adaptive in 2050, there is a need for research on heat stress in the current and future climate.

The main research question of this study reads: ‘What is the influence of vegetation on heat stress in current and future climates in Rotterdam, the Netherlands?’

In order to formulate a complete and substantiated answer to the main research question, four sub questions will be answered. The sub questions read:

1. In what way does vegetation influence heat stress?
2. What is the current situation of heat stress in Rotterdam?
3. What is the prospect for future heat stress in Rotterdam considering climate change?
4. What is the effect of vegetation on current and future heat stress in Rotterdam?

To understand in what way vegetation can affects heat stress, a literature review will be carried out. To analyse the heat stress in Rotterdam, model runs will be performed. The heat stress is assessed by the calculation of PET and its spatial variability in Rotterdam with an empirical regression model. The model is used to calculate different PET-maps, each related to one of the last three sub questions. The PET is calculated with the use of different elements, which can all be analysed individually. By doing this, insight in the different factors influencing the PET are described. The calculation of the PET is based on a regression heat balance model.

The model that is used in this study is called Tygron Geodata Platform, developed by Tygron, a Dutch software company. The Tygron Geodata Platform will be referred to as Tygron in this study. The quantitative physically based model is used to generate PET maps of the study area. To study the current heat stress in Rotterdam, the heat overlay is used with climatological data of multiple days with maximum temperatures that have varying return periods. (Koninklijk Nederlands Meteorologisch Instituut, 2022). To see how heat stress will develop under climate change, downscaled climatological input for 2050 and 2085 of a specific climate change scenario is used as input in the heat overlay. To analyse the effect of vegetation on heat stress in the current and future climate of Rotterdam, the presence of trees will be modified to create new spatial input for the heat overlay. Differences and similarities between the various model outputs will be compared to each other to analyse the effect of each of the changing inputs on the model outputs. Also, the different model results will be tested against the guidelines for climate adaptive cities. Earlier research proposed certain guidelines a climate adaptive city should meet to be heat stress resistant (Kluck et al., 2020). Two of these guidelines are that all households should be in the proximity of a 'cool place' and main walking routes should have enough shade throughout the hottest hours of the day. The model results will be tested against these guidelines to indicate how the climate adaptivity between the different model runs varies.

Previous research has shown that increasing the vegetation cover can lower the air temperature on a local scale (Dimoudi & Nikolopoulou, 2003; Giridharan et al., 2008; Susca et al., 2011). Some studies even state that planting trees in an urban area may be one of the most important strategies to improve the urban thermal environment (Ren et al., 2022). However, it is expected that the effect of vegetation is not large enough to cool down the climate. It is expected that in the current situation in Rotterdam, considerable heat stress is experienced. Earlier research on other Dutch cities has shown that heat stress is present, especially on hot summer days (Brink, 2020; Ren et al., 2022). Rotterdam is expected to be no exception. It is assumed that climate change will increase heat stress in Rotterdam in the future. It is also expected that when increasing the number of trees present in Rotterdam, the physiological equivalent temperature will decrease on locations with trees, compared to the physiological equivalent temperature on the same location but without trees. This is because the cooling effects of vegetation are assumed to outrange the warming effects. It is predicted that adding more trees in Rotterdam will have a positive influence on reducing heat stress for inhabitants, in current and future climates. It is not expected that adding trees will be enough to reduce heat stress substantially, however it is a method that helps in mitigating heat stress that is relatively easy and financially viable for municipalities to implement.

This thesis is organized as follows: in Chapter 2 the literary review is presented, explaining the relevant processes that are studied in this thesis and how vegetation and heat stress are related to each other. In Chapter 3, the methodology of the model simulations is explained. Chapter 4 presents the results of the model runs. Chapter 5 reflects on the findings and discusses the modelling approach, and in Chapter 6 the conclusions are drawn.

2 Background

2.1 Using PET instead of air temperature

As mentioned in Chapter 1, the processes driving vegetation and temperature involve many feedback mechanisms. To understand what the effect of vegetation on heat stress is, a clear definition of heat stress and physiological temperature is required. Therefore, a description of why this study uses physiological equivalent temperature rather than temperature is given first. Thereafter, the standards and equations describing the PET are explained, followed by how PET and physiological stress are related.

The PET is not the same as air temperature, which is given in weather forecasts, for example. The air temperature indicates the measured temperature of the air outside. The PET is a thermal index in degrees Celsius, derived from the human energy balance. The PET is the temperature a person experiences as a result of multiple factors, including air temperature, given in the physical unit degrees Celsius (Matzarakis et al., 1999). To give an example, when the air temperature is 30 °C, the PET in the sun, outside of the wind, can be experienced as high as 40 °C. Not only environmental factors, such as radiation, wind and humidity influence the PET, but also personal factors influence how the PET is experienced by a person. PET can be calculated from a heat balance model that is based on heat exchange of a reference body (de Nijs et al., 2019). The reason this study and many others assess heat stress for populations or societies with the physiological equivalent temperature rather than with direct measurements or calculations of the atmospheric temperature is that PET can directly related to levels of physiological stress. When thermal discomfort of a society is established, as it is in this study, all factors contributing to the thermal comfort need to be taken into account. The functioning of the human body depends on the amount of thermal stress the body experiences, which depends on the PET. Therefore, if only the air temperature is used, many important factors that are of direct impact on the functioning of a body are neglected.

2.2 Quantifying the PET

2.2.1 PET and the energy balance of the human body

The theory of the physiological equivalent temperature is based on the energy balance of the human body. When this energy balance is not in equilibrium, a person can experience ‘heat’ or ‘cold’. Values of PET are established on a person’s perception of the temperature, which is a result of the energy balance of a person’s body being in or out of equilibrium. The Munich energy balance model for individuals (MEMI), can be seen in Equation 1 (Höppe, Peter R., 1993).

$$M + W + R + C + E_d + E_{Re} + E_{Sw} + S = 0 \qquad \text{(Eq. 1)}$$

Where:

- M is the metabolic rate, which is an indication of the internal energy production by the oxidation of nutrition (this term is always positive)
- W is the physical work output (this term is always negative). This factor is not influenced by a meteorological parameter.
- R is the net radiation of a body. This is influenced by the mean radiant air temperature.
- C is the convective heat flow. This is influenced by the air temperature and the air velocity of wind.
- E_d is the latent heat flow, which is an indication of the evaporation of liquid into vapour, in this study the transition of water is from the skin into the atmosphere (this term is always negative). This factor is influenced by the humidity of the atmosphere.
- E_{Re} is the sum of heat flows for warming and humidifying air. The $\mathrm{E_{Re}}$ is influenced by the air temperature and humidity.
- E_{Sw} is heat flow from the evaporation of sweat (this term is always negative). This term is influenced by the air humidity and velocity of wind.
- S the storage heat flow, for warming and cooling of the body.

In general, the units of the terms are expressed in Watt. If a term in this energy balance is positive, there is gain in energy. When a term is negative, there is energy loss.

2.2.2 Environmental factors influencing PET

The PET can be quantified with different methods by using various equations. Approximately all methods are based on the energy balance of the human body. This study carries out calculations of PET according to the method proposed by the National Institute for Public Health and the Environment (RIVM) (de Nijs et al., 2019). The factors that influence the heat balance of the human body can be divided into two groups: the first group is the one with all personal factors, ranging from the characteristics of the human body and the processes within it, to a person's activity and clothing (Chen, Y. & Matzarakis, 2014). The components of the energy balance of the human body that are seen as personal factors are: the metabolic rate, the physical work, the net radiation of a body, the heat flow from the evaporation of sweat and the storage heat flow. These personal factors are different for each person. The second group are the environmental factors. The environmental components of the energy balance of the human body are the convective heat flow, the latent heat flow, the sum of heat flows for warming and humidifying the air (Equation 1).

This study will focus mainly on the second group of factors, environmental factors that influence the energy balance of the human body, as the exposure of a group of people is assessed in this study, instead of the exposure of one individual. The most important environmental factors that determine the PET are air temperature, wind, shade, and humidity. These factors are influenced by each other as well as by other environmental factors. For example, whether a surface is shaded or in direct sunlight directly influences the PET itself, but it also influences the air temperature, because the solar radiation can warm up surfaces, which can emit this warmth into the air, warming up the atmosphere. This air temperature rise also affects the PET. The processes that are of direct influence on the PET are interconnected and influence each other. When considering PET for groups of people or for a population, like in this study, instead of for individuals, standard values are calibrated for the personal factors in the energy balance of the human body.

The factors that influence the PET is equal to the initial information required to calculate the PET with the method of the National Institute for Public Health and the Environment (blue boxes, Figure 1). These factors are:

- Land use
- Vegetation
- Atmospheric temperature
- Solar radiation
- Surface elevation
- Structures (buildings, trees, bridges et cetera)
- Wind speed and direction
- Atmospheric transmissivity
- Humidity

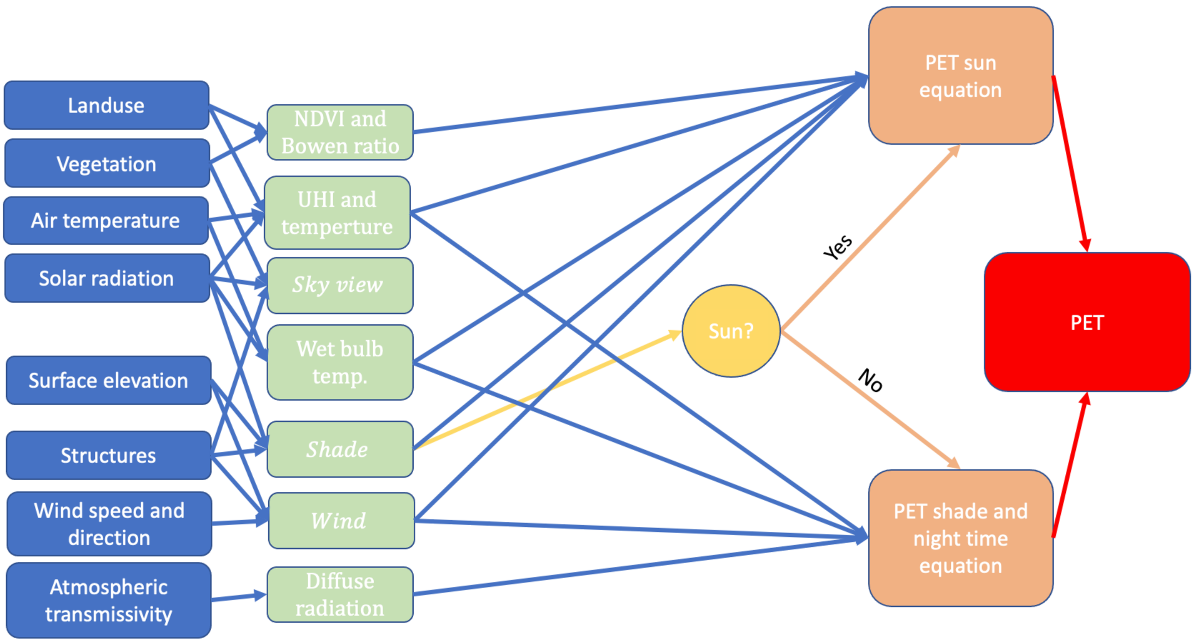

Figure 1: Flowchart of calculation of PET and factors influencing PET. In blue all environmental factors are shown, their arrows point to the intermediate steps (green). Whether a location is in direct sunlight or not depends which equation is used to calculate the PET. Based on Figure 3.5 of De Nijs et al, flowchart of the Heat Stress Test (De Nijs et al., 2019).

2.2.3 Intermediate calculations

The intermediate calculations are shown in the green boxes in Figure 1. The intermediate calculations use the initial information and sometimes the results of other calculations to determine the values that are then used for the calculation of the PET. An overview of the different intermediate calculations is given here.

NDVI and Bowen ratio

The normalized difference vegetation index is calculated for the study area with an aerial photo, to determine the presence of vegetation at certain locations. This calculation also determines the vegetation fraction, which is used in the calculation of the UHI. The Bowen ratio (B_b) is a surface property, therefore it's value in the model is based on the land use as well as the presence of vegetation. The presence of trees also affects the Bowen ratio. The model assigns a Bowen ratio of 0.4 [-] to surface area that contains vegetation and surface area without vegetation is given a Bowen ratio of 0.3 [-].

Sky view factor

The sky view factor (S_{vf}) is the ratio between the received radiation on a planar surface and the emitted radiation by the hemispheric environment. It describes how much the sky is visible from a certain surface location. When the sky view factor is calculated for a certain cell, structures that block the view, such as buildings and trees are taken into account. The sky view factor has no unit [-].

Urban heat island (UHI) and atmospheric temperature

The maximum UHI is calculated over a study area with the use of the sky view factor and the vegetation fraction. The calculation can be seen in Eq. 2. With the use of the UHI and climatological data, the atmospheric temperature (T_a) in the study area is calculated for each location. This calculation is shown in Eq. 3. The UHI and atmospheric temperature are location dependent. The daily maximum urban heat island effect is calculated with the following diagnostic equation (de Nijs et al., 2019; Theeuwes et al., 2017).

$$UHI_{max} = (2 - S_{vf} - F_{veg} \sqrt[4]{\frac{S\left(T_{max-T_{min}}\right)^3}{U}}) \qquad \text{(Eq. 2)}$$

In this equation (Eq. 2), the sky-view factor (S_{vf}), the vegetation fraction (F_{veg}, determined by the NDVI) define the environment and the hourly global radiation (S) in Wm^{-2}, the daily average wind speed (U) in ms^{-1} together with the minimum (T_{min}) and maximum (T_{max}) daily temperatures in °C define the weather conditions. Together, they are used to calculate the daily maximum UHI [°C].

The local hourly air temperature $T_a[h]$ is calculated in °C with Equation 3 and uses the temperature $T_{station}$ of the nearest weather station. The $daily\ variation\ UHI[h]$ and the UHI_{max} together with the temperature measured at the weather station are used to calculate the local temperature in the study area for each hour.

$$T_a[h] = T_{station} + UHI_{max} * daily\ variation\ UHI[h] \qquad \text{(Eq. 3)}$$

Wet bulb temperature

The wet bulb temperature is calculated with the KNMI weather station data. The adiabatic saturation temperature is calculated with the atmospheric temperature and the sun altitude angle, and several solar constants sourced from the DRPA heat stress report (de Nijs et al., 2019).

Shade

The shade is calculated with information from the digital elevation model, buildings, trees, and other structures. Together with information about the solar altitude angle (φ) and radiation, the shade in the study area is calculated.

Wind

Another intermediate calculation that is carried out before the calculation of the PET is carried out is the wind speed. Wind speed is measured at weather stations, which are often located on a grass field in a rural environment. The wind speed is transformed to the urban environment at a height of 1.2 meters with a set of calculations. Not all the transformations are shown here, however the most important products of the transformations can be seen in Equation 4 and 5. The wind speed [ms^{-1}] at 1.2 meter above the surface is calculated with the wind at building height (u_H), height H [m], and λ [m], which is a function of the frontal area density (λ_f). The frontal area density [-] depends on the density and size of objects pointed perpendicular to the wind. The wind speed at 1.2 meters ($u_{1.2}$) is what is entered in the empirical PET equation, in ms^{-1}.

$$u_{1.2} = u_H \exp(9.8\lambda\left(\frac{1.2}{H} - 1\right)) \qquad \text{(Eq. 4)}$$

Diffuse radiation

The diffuse radiation (Q_{diff}) is calculated with the global radiation (Q_{gl}) and the atmospheric transmission factor at a certain time. This factor considers all of the radiation that is received in a certain cell from scattered or reflected radiation. Diffuse radiation and can be received at locations in direct sunlight as well as locations in the shade. The equation to calculate the diffuse radiation in Wm^{-2} is shown in Equation 5. τ_a is the atmospheric transmissivity [-], which is also defined by the global radiation and the suns position. The global radiation is the sum of one hour of measured solar radiation in Wm^{-2}.

$$\frac{Q_d}{Q_{gl}} = \begin{bmatrix} 1, & \tau_a < 0.3, \\ 1.6 - 2\tau_a, & 0.3 < \tau_a < 0.7 \\ 0.2, & \tau_a > 0.7 \end{bmatrix} \quad \text{where } \tau_a = \frac{Q_{gl}}{1367\sin(\varphi)} \qquad \text{(Eq. 5)}$$

2.2.4 PET calculations

After the initial information and intermediate calculations are carries out, the actual PET can be determined. There are two empirical equations for calculating the PET for each hour of the day, one for locations directly in the sun and another for locations in the shade or during night-time. The inputs to these equations are listed below and described in the previous section.

The PET for shaded locations or calculations during night-time is calculated with:

$$PET_{shade,night} = 12.14 + 1.25T_a - 1.47\ln(u_{1.2}) + 0.060T_w + 0.015S_{vf}Q_{diff} + 0.0060\left(1 - S_{vf}\right)\sigma(T_a + 273.15)^4 \qquad \text{(Eq. 6)}$$

The PET for locations in direct sunlight is calculated with:

$$PET_{sun} = -13.26 + 1.25T_a + 0.011Q_{gl} - 3.37\ln(u_{1.2}) + 0.078T_w + 0.0055Q_{gl}\ln(u_{1.2}) + 5.56\sin(\varphi) - 0.0103Q_{gl}\ln(u_{1.2})\sin(\varphi) + 0.54B_b + 1.94S_{vf} \qquad \text{(Eq. 7)}$$

The terms in these equations refer to the factors described in the section above. For simplification, the definitions and units are listed below:

- T_a is the air temperature at 2 meters above the ground [$°C$]
- T_w is the wet bulb temperature [$°C$]
- $u_{1.2}$ is the wind speed at 1.2 meters above the ground [$m\ s^{-1}$]
- S_{vf} is the sky-view factor [-]
- Q_{diff} is the diffuse radiation [$W\ m^{-2}$]
- Q_{gl} is the global radiation [$W\ m^{-2}$]
- σ is the Stefan Boltzmann constant [$Wm^{-2}K^{-4}$]
- φ is the solar altitude angle [-]
- B_b is the Bowen ratio [-]

The parameters in this method are validated on Wageningen, the Netherlands. The reference body for this to calculation of the PET is a thirty-five-year-old male dressed in reference attire with a certain thermic permeability. The reference body's effort level is equivalent to an average walking speed; 4 km/h (de Nijs et al., 2019).

2.3 PET and level of physiological stress

Heat stress is defined as the effects of exposure to heat. Because heat is affected by more than only air temperature, PET is often used to assess heat. PET and heat stress are directly related to each other. Exposure to certain values of PET is defined as the cause, and heat stress is defined as the result. The PET for a person is correlated to the thermal perception by that person, which correlates to stress on internal heat production. The latter is interpreted as 'heat stress' (Matzarakis et al., 1999). As mentioned before, heat stress occurs when a body is exposed to heat for a period of time where the body cannot release heat anymore. Heat stress is directly linked to the PET; when the PET of a certain person is experienced at certain values, corresponding levels of heat stress occur. The PET is a standardized representation of the degree of heat stress experienced by a standard person. The same accounts for situations where experienced temperatures are very low, in which cases cold stress can occur. According to the RIVM, the probability of heat stress increases from a physiological equivalent temperature of 23 ℃ and higher. As can be seen in Table 1, specific ranges of physiological equivalent temperature are classified according to human thermal comfort levels, or grades of physiological stress. The heat stress classes that are relevant to this study are defined as follows: slight heat stress, moderate heat stress, strong heat stress and extreme heat stress (de Nijs et al., 2019).

PET [℃]	**Thermal perception**	**Level of physiological stress**
< 4	Very cold	Extreme cold stress
4 – 8	Cold	Strong cold stress
8 – 13	Cool	Moderate cold stress
13 – 18	Slightly cool	Slight cold stress
18 – 23	Comfortable	No thermal stress
23 – 29	Slightly warm	Slight heat stress
29 – 35	Warm	Moderate heat stress
35 – 41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

Table 1: Different levels of perception of thermal physiological stress on internal heat production of humans with their different ranges for physiological equivalent temperature (de Nijs et al., 2019).

2.4 Heat stress in the urban environment

The urban heat island, as mentioned in section 1, is a phenomenon that occurs due the effect where the urban environment has a higher temperature than its rural surroundings. The urban heat island effect is strongest when there is little to no wind and the weather is sunny. Urban constructions cause cities to have a complex canyon structure, or high rugosity, which leads to a small albedo factor, which means incoming radiation is not as much reflected as it is taken in. In addition, urban constructions block and reduce the speed of winds. All this causes an alteration in the radiation balance of urban areas (Steeneveld et al., 2011). Besides the alteration in the radiation balance, urban areas have more factors that influence the overall energy balance differently compared to rural areas. In cities, the population density is much higher than in its surrounding areas, which leads to relatively large anthropogenic heat release (Koopmans et al., 2018). This anthropogenic heat release is caused by human activity. Also, cities typically have a lower vegetation density (Dimoudi & Nikolopoulou, 2003). This is one of the reasons for the relatively low sky-view-factor and low evaporation heat flux. Cities are able to store heat due to the relatively high thermal capacity and heat conductivity. The incoming heat is stored during the day and released during the night, causing the relative increase in temperatures to be most severe at night-time, compared to the rural surroundings. An elevated temperatures at night can cause health problems because it affects sleep and recovery from heat during the day in a negative way (Hsu et al., 2021).

2.5 The role of vegetation on heat stress

Vegetation plays an important part considering heat in urban areas. Vegetation such as trees influences the air temperature not only directly, but also the PET is influenced by the presence of vegetation (Ren et al., 2022). One of the processes related to vegetation is evapotranspiration. An increase in evapotranspiration causes relatively less latent heat, which directly influences the atmospheric temperature (Dimoudi & Nikolopoulou, 2003). Vegetation can also influence the PET by offering shade to humans. Moreover, by creating shade, incoming heat from solar radiation is not able to warm up the underlying ground, which affects heat emittance from the ground to the air during the night.

Vegetation is characterized by leaves and branches. Because of this, vegetation has the ability to block incoming radiation from reaching the area behind the canopy. This directly affects the PET, as being in the sun leads to a higher PET than being in the shade, as well as the temperature of the surface underneath the canopy. Warm ground can warm the temperature of the air above it, which also affects the PET. The amount of solar radiation blocked by the canopy depends on the vegetation type. Scrubs and grasses generally block less radiation than trees, due to their relatively large canopy size and density. Therefore, in this study the focus is on the effect of trees on air temperature. The amount of solar radiation blocked by tree canopy is also seasonally dependent. Generally, trees prevent ninety to seventy percent of the solar radiation from reaching the ground beneath a tree during the summer. In winter, only ninety to twenty percent is blocked. This difference is caused by the fact that deciduous trees lose most of their foliage in fall (Oke, 2010). An important effect of shade is that is reduces surface temperatures. Hot surfaces emit heat into the atmosphere. During the day, a surface can heat up, and then later transmit this heat during the night-time into the atmosphere. Shaded areas beneath trees do not warm during the day, so there is no heat exchange warming the atmosphere during the night.

Another vegetation related process that influences the atmospheric temperature is evapotranspiration. Evapotranspiration is a term used for the process where water transfers from the soil to the atmosphere trough transpiration and evaporation. For vegetation, transpiration is the most important process in releasing water (Dimoudi & Nikolopoulou, 2003). The process starts when water is taken up from the soil by the roots. As water moves through the plant, it serves critical functions within the plant tissue. The final step in this process is that water leaves the plant as vapour through the stomata on the leaf surfaces. Processes that influence the evapotranspiration are vegetation type, soil type, soil saturation, availability, and intensity of radiation from sunlight, land slope, atmospheric temperature, wind and air movement, precipitation and humidity of the atmosphere (Dimoudi & Nikolopoulou, 2003). The other process that belongs to evapotranspiration, evaporation, is also influenced by vegetation. Evaporation can occur on the land surface around a plant or tree, or directly from the leaves and other surfaces of vegetation. Evapotranspiration reduces the temperature of the atmosphere because the process requires heat energy. This heat energy is taken from the atmosphere by molecules for the conversion into another phase, thus from liquid water to water vapour in the case of evapotranspiration. The heat taken from the atmosphere cools the air temperature. This heat that is taken from the atmosphere is sensible heat, which is transferred into latent heat (phase change).

Shading together with evapotranspiration has a cooling effect on the air temperature. Because of these two processes, vegetation has the possibility to lower peak temperatures in the urban environment.

Large vegetation such as trees or shrubs can block winds that blow perpendicular to their surface. The blocking of wind also affects the PET. Sometimes, blocking wind can have positive effects, for example near large constructions in the urban environment. At these locations, winds can be pushed into narrow crevices between buildings, causing strong winds with high velocities. However, wind generally has a positive effect on evapotranspiration and cools down the PET. Therefore, too much vegetation could have a negative effect due to slowing down and blocking air flow. Also, where the wind is originated from plays an important part in this matter. Winds from dry and cool areas have very different effects on evapotranspiration and PET compared to winds from warm and wet areas (Huang et al., 1987). Winds from dry and cool areas tend to increase the rate of evapotranspiration from vegetation. This is because these winds have a low water vapor content and a high capacity to absorb moisture. Winds from warm and wet areas tend to decrease the rate of evapotranspiration from vegetation. This is because these winds have a high water vapour content and a low capacity to absorb moisture.

3 Methodology

3.1 Research area

Rotterdam is a large harbour city in the West of the Netherlands. It is the second largest city in the Netherlands in population numbers. The manmade Nieuwe Maas flows through the large canal called Nieuwe Waterweg flowing from the West of the city through Rotterdam as the Nieuwe Maas ending up in a river called the Lek. This river stems from the river Meuse. Rotterdam was chosen as a research area because it is located in a large, urbanized area in the Netherlands, the Randstad, where there is great demand for scientific research on heat stress related to climate change. Rotterdam has over 650,000 inhabitants. Rotterdam is one of the most densely populated areas of the Netherlands. The climatological conditions of the study area are characterized by the vicinity of the North Sea. The prevailing wind direction is from the southwest. This region of the Netherlands characterized by its temperate maritime climate, indicated by the letter code ‘Cfb’ within the Köppen-Geiger climate classification system. On an average yearly basis, Rotterdam receives a little over 800 millilitres of precipitation. Approximately twenty summer days occur, where the air temperature is more than twenty-five degrees Celsius, as well as a few tropical days, where the air temperature is over thirty degrees Celsius. It is on these days where the most heat stress occurs.

The municipality of the study area aims for Rotterdam to be a climate adaptive city by 2050. The three suggested guidelines which a climate adaptive city should meet are (Brink, 2020; Kluck et al., 2020):

1. Distance to cool places; every residence should have access to cool place within walking distance. Cool places are locations where citizens can go to find shelter from heat stress during extremely warm temperatures. A cool place is a shaded area of at least 200 m^2 of publicly available space, where the PET is continuously below 38 ℃ during an average summer day. A cool place is required to have seating opportunities, as well as swimming areas or fountains.
2. Shade on walking routes; important walking routes should be shaded during the sunniest moment of the day must be at least 40%.
3. Minimum percentage of green: Depending on the type of district, a certain percentage of vegetation should be met.

These guidelines can be used to test whether a city is climate adaptive in the current of expected future climate.

The research area is located in the centre of Rotterdam and is 100 square kilometres in size (Figure 2 & 3). About 36.1% of the surface of the study area is water, which is mostly the river Meuse. According to the BAG, 16.6 % of the study area consists of residential buildings. This means that 47.3% of the study area is open space which is accessible for humans and where people can be exposed to heat stress, besides their personal residents.

The last part of the study is executed on a smaller research area, within the original study area. This area is a neighbourhood called Rotterdam West (Figure 4). In Rotterdam West, a stream of water is located in the middle of the study area, which is orientated north-south. Four bridges can be found that cross the water. Along the water, a park is located. In the south of the study area, a square can be found. Approximately 56.1% of the study area is considered accessible open space, which theoretically can be reached by citizens.

Figure 2: The agglomeration of Rotterdam and the study area shown in the square shape in the middle of the map (Scale 1:200,000) (Kadaster, Esri, HERE, Garmin, GeoTechnologies Inc., USGS, METI/NASA, NGA)

Figure 3: The Netherlands with the study area highlighted in pink. (Scale 1:2,000,000) (ESRI, HERE, Garmin, FAO, USGS)

Figure 4: Rotterdam West. (Scale left 1:200,000, right 1:20,000) (ESRI, HERE, Garmin, FAO, USGS & Google Maps, 2023)

3.2 Description of Tygron

The software used in this study to determine the heat stress in Rotterdam is the Tygron Geodesign Platform (Tygron), developed by the Dutch company Tygron. Tygron is an open infrastructure platform that can automate complex spatial information. In Tygron, it is possible to visualize, process, calculate, optimize and analyse large amounts geo data (vector and raster data). By default, the Tygron connects to open data sets to visualize a chosen area as a three-dimensional digital twin. Tygron can visualize different scenarios in a chosen area by using calculations and machine learning in order to aid decision making, for example for municipality issues. Tygron was chosen because of its ability to process sophisticated and detailed urban morphological data and the ability to develop future designs for urban areas. In these future designs, changes can be made to an urban area, for example in the construction of buildings and vegetation. Tygron contains a standard heat overlay for calculating physical equivalent temperature in urban environments. With this heat overlay, PET maps can be created. The Heat Overlay contains two modules that both use a different method to calculate the PET. The first module is more basic module that is based on global standards for the assessment of PET, called UNSECO. The second module, called the DPRA Heat Stress Module, simulates the physical equivalent temperature in urban areas based on the report of the Dutch National Institute for Public Health and the Environment (RIVM) on the Standard Heat Stress Test. This report was developed to provide a standard in the calculation and approach of heat stress for Dutch municipalities. The DPRA Heat Stress module is designed especially for Dutch standards and is much more detailed and comprehensive than the UNESCO module. The flowchart describing the method of the PET calculations in Tygron is directly based on the DPRA Heat Stress Module of the RIVM (Figure 5). The PET is calculated by using local parameters and geographical features.

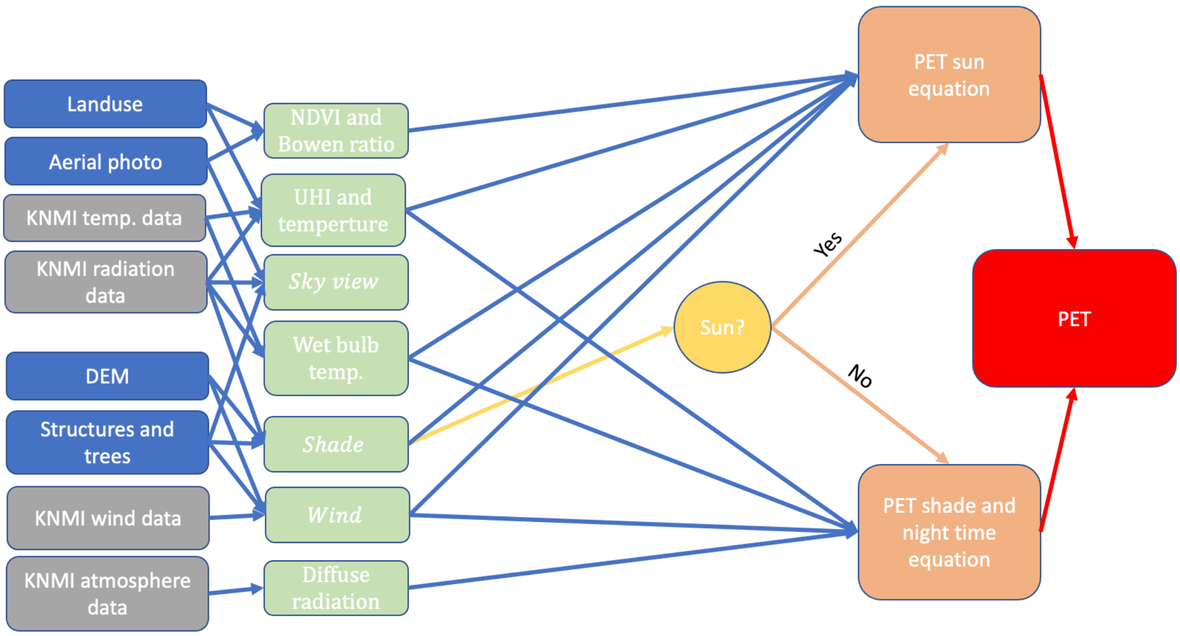

Figure 5: Flowchart of the inputs and the method for the calculation of the PET (De Nijs et al., 2019). The blue boxes represent the spatial input data, the grey boxes represent the meteorological input data, and the green boxes represent the intermediate calculations.

3.2.1 Data input

The meteorological data used in this study is point-data that originates from KNMI weather station 344, Rotterdam, the Netherlands (Table 2). This data originates from a single point location and is translated for the entire study area by the use of interpolation. The spatial input data originates from different data sources, a description of the spatial input data is shown in Table 3. All data used in this study is from open sources.

Meteorological input data:	**Description and temporal resolution:**
Sun angle, altitude and azimuth	Calculated by Tygron, based on day, time and location of model run. Used to determine shade at a certain location considering buildings, vegetation and other sun blocking structures. *Hourly and daily average*
Air temperature	The air temperature is automatically interpolated from the weather data of the entered day, time and location of the nearest KNMI weather station. *Hourly, daily maximum, minimum and average*
Global radiation	The global radiation is automatically linked to the weather data of the entered day, time and location of the nearest KNMI weather station. *Hourly and daily average*
Humidity	The humidity is automatically linked to the weather data of the entered day, time and location of the nearest KNMI weather station. *Hourly*
Wind speed	The wind speed is automatically linked to the weather data of the entered day, time and location of the nearest KNMI weather station. *Hourly and daily average*
Wind direction	The wind direction is automatically linked to the weather data of the entered day, time and location of the nearest KNMI weather station. *Hourly*

Table 2: Meteorological input data and their temporal resolution.

Spatial input data:	**Description and source:**
Land use	Information on different land use in the form of classes. *Source:* *BGT* *1 meter*
Structures	Information on buildings, bridges and other structures in the study area. *Source:* *BGT* *1 meter*
Aerial photo	An orthophoto containing information on its RGBI bands. *Source:* *PDOK, Ortho10 2016* *10 meters*
DEM	Digital elevation model of the study area. *Source:* *AHN4* *0.5 meter*
Trees	Information on the location and foliage height of trees is combined from two different data sets. *Source:* *Tree locations: BGT, 1 meter* *Tree foliage height: AHN4, 0.5 meter*

Table 3: Spatial input data with their source and spatial resolution.

3.2.2 Calculation of PET

The exact method of the calculation of the PET in Tygron is explained in Section 3.3.3 and 3.3.4. The calculations are done as snapshots of each hour, they do not show an accumulation or average of the PET of the (past) hour. The calculation of PET differs for locations that are directly in the sun compared to locations that are not in the sun (cells in the shade and calculations at night), as explained in the previous chapter.

In Tygron, settings and input can be set in the Configuration Wizard. An overview of the settings, data configuration and input parameters in the heat module is given here. Apart from the data input in the model for this study, certain configuration settings must be set in Tygron before running the DPRA heat stress module. The first setting is the grid cell size, in this study the grid cell size was set to 1 meter. The second setting is the day and time at which the model must run. The DPRA Heat Stress Module calculates the PET over the entire study area except for buildings and water. Because in this study the heat stress in Rotterdam is assessed for different climatological and spatial circumstances, some configuration settings differ per model run. The specific input and settings for each of the model runs is given in Section 3.3.

3.3 Model runs

To understand what the influence of vegetation on heat stress in current and future climates in Rotterdam is, besides a literature study, multiple model runs are done. In each of the model runs inputs or settings in Tygron's heat stress overlay are altered. The model runs multiple times, each time the model's input and settings are based on the assessment of one of the following three sub questions:

1. What is the current situation of heat stress in Rotterdam?
2. What is the prospect for future heat stress in Rotterdam considering climate change?
3. What is the effect of vegetation on current and future heat stress in Rotterdam?

In the following sub sections, the exact input and settings are described for each of the sub questions.

To provide a proficient image of the heat stress in Rotterdam, the spatial distribution of PET in the study area as well as the exposure of citizens to heat stress is assessed. To assess the exposure of citizens to heat stress in Rotterdam in the current and future climate, the outcomes of the different model runs will be tested against interpretations of guidelines 1 and 2 of Section 3.1. Also, the average PET at certain distances of residential buildings will be calculated, to show at what PET a person could be exposed when leaving their home on a summer day. The PET inside the home of citizens is not assessed in this study. This study assesses the exposure of citizens to heat stress on the public surface area.

To assess the current heat stress in Rotterdam as well as future heat stress and the effect trees have on heat stress, it is important that only certain inputs are adjusted during the model runs, while other inputs stay the same in each model run. Otherwise, differences between the model runs cannot be related to changes in input. The two most important factors that remain the same in all model runs are the humidity, solar radiation and wind speed in the study area. The values of these inputs can be seen in Table 4.

Input factor	**Value**
Solar radiation [W/m^2]	700
Humidity [%]	60
Wind speed [m/s]	3

Table 4: Fixed input values in all model runs.

3.3.1 Current heat stress in Rotterdam

Model run 1 is carried out to study the current heat stress in Rotterdam. To study the current heat stress, the PET is calculated with climatological circumstances that occur in Rotterdam with different return periods. The spatial input that resembles the current situation is used, and no further adjustments are made to the model settings or the input. The aim of this model run is to see how the PET in Rotterdam is spatially distributed for different types of summer days.

For the assessment of current heat stress in Rotterdam, hot days with different return periods are used as climatological input. The return periods, or recurrence times, of maximum daily temperatures of summer days are calculated with the KNMI weather data of the weather station of Rotterdam, KNMI weather station 344. The return periods of maximum daily temperatures are calculated with the following equation:

$$Recurrence\ time = \frac{T+1}{rank} \qquad \text{(Eq. 8)}$$

To calculate the recurrence time or return period for maximum daily temperatures with Equation 8, T refers to the total number of maximum daily temperature measurements in the dataset, disregarding hiatus. In Equation 8, $rank$ is the rank from highest to lowest daily temperature of the available measurements. The KNMI weather station of Rotterdam (station code 344) has recorded climate data since 1961. The recurrence time indicates how often a certain maximum temperature is reached or exceeded. In general, recurrence times (or return periods) refer to the average time interval between events of particular magnitude or intensity. The recurrence periods are calculated with maximum temperatures of climate data from, which refer to recorded climate data from the dataset. Meaning that each return period has a reference day, that can be used as input in Tygron. By running the model for various maximum temperatures, the PET can be calculated for moderate summer days, that occur yearly, and for hotter summer days, that occur once every few years. In this study, to study the heat stress in the current climate, hot days with a maximum daily temperature with return periods of 33 years, 5.5 years, 3 years and 1 year are used. To study how heat stress develops in the future climate, maximum daily temperatures with a return period of 3 years are used for the current climate, the expected climate in 2050 and 2085. This will be explained further in section 3.3.2.

Because the four summer days vary in air temperature as well as in wind direction, a small analysis of the effect of both factors on the pattern of the PET is carried out. For this analysis, the difference in the pattern between the summer day with the longest return period, according to their maximum daily temperature, and the summer day with the shortest return period is determined. This is done by dividing the PET calculations of the summer day with a return period of 33 years by the PET calculations of the summer day with a return period of 1 year. This map will indicate whether the patterns of the two PET calculations differ from each other or not. Next, to assess the effect of wind direction on the PET, for one of the reference days, the wind direction will be altered to the perpendicular and opposite directions. By doing this, for the summer with a return period of 5.5 years, the PET will be calculated for four different wind directions. The results of this analysis will give more insight in whether the wind direction influences the PET and if the pattern of the PET will differ for different summer days.

3.3.2 Future heat stress in Rotterdam

To make estimations of what the prospect for future heat stress in Rotterdam could be considering climate change, changes are made to the meteorological input data. Tygron allows editing the specifics of the meteorological input of past days in the Configuration Wizard. For the assessment of heat stress in future climates, the PET is calculated for downscaled future climate data of the Netherlands (KNMI, 2021).

The Royal Netherlands Meteorological Institute (KNMI) published four climate change scenarios for the Netherlands, called the KNMI'14 scenarios (KNMI, 2014). The four climate change scenarios are based on the global climate change estimations of the Intergovernmental Panel on Climate Change (IPCC, 2014). The KNMI'14 report contains downscaled future daily climate data of the four climate scenarios for multiple Dutch weather stations in 2050 and 2085 (Attema et al., 2014).

Four alternative scenarios have been created, because there are various uncertainties involved in projecting climate change. How the climate will develop over time remains uncertain, and for now it is anticipated to be a combination the four scenarios (Attema et al., 2014). The scenarios are arranged as follows; there are two G-scenarios, for which the global temperature rise is assumed to be 1 °C for 2050, and there are two W-scenarios, which assume a global temperature rise of 2 °C . A global description of the four scenarios is shown in Figure 6. The W-scenarios match the IPCC high emission scenario, RCP8.5. The G-scenarios are based on the RCP4.5 and the RCP6 scenarios, which are on the lower end of the emission scenario prediction (Koopmans et al., 2018; Nakicenovic et al., 2000). For both temperature-rise scenarios, a distinction is made between the degree of change within the air circulation. The scenarios with low values of change within the air circulation are the G_L- and W_L-scenario, and the scenarios that consider high change in air circulation patterns are the G_H- and W_H-scenario. The expected change in air circulation can have a considerable influence on climate change. In this study, the climate data for the assessment of the future heat stress in Rotterdam is based on the W_H-scenario. For the W_H-scenario, air temperature is expected to rise with 2 °C by 2050, and the high change in air circulation patterns will cause high pressure systems to have a large influence, which will lead to an increase in Eastern winds. For the Netherlands, this will likely lead to the conclusion that drier and warmer summers can be expected (Huynen & Martens, 2015).

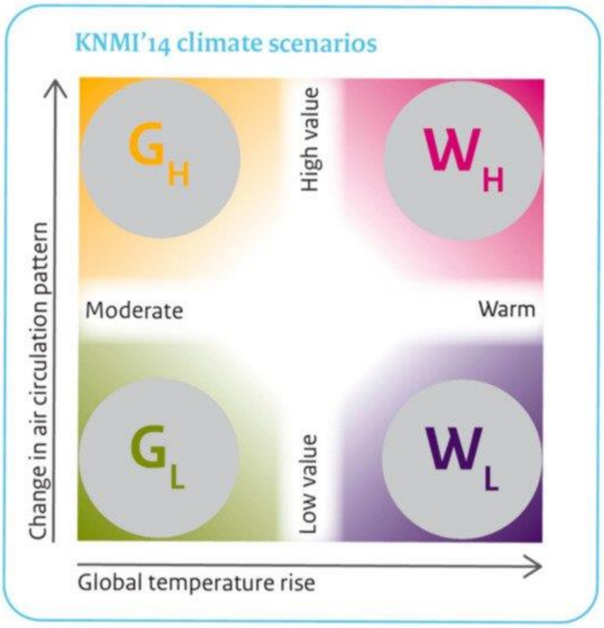

Figure 6: The four KNMI'14 climate scenarios for the development of the climate in the Netherlands until 2100 AD (Koopmans et al., 2018).

The W_H-scenario is the 'worst-case' climate change scenario, with the highest air temperature rise and highest change in air circulation patterns. This scenario is used because it captures the highest potential future risks. For 14 weather stations in the Netherlands, data from the reference period from 1981 to 2010 has been transformed for the KNM'14 scenarios. The KNMI'14 data is open source (KNMI, 2021).

Because the input in this model run is a prediction, for the assessment of future heat stress a hypothetical hot day is used as input. In the transformed future climate data, daily maximum temperatures are available. The transformation method for maximum daily temperatures in the future climate was developed by the KNMI itself, the same institution that provides the ready-to-use transformed climate data (KNMI, 2014). In this part of the study, already transformed climate data is used as an input into Tygron. To assess heat stress in Rotterdam in the future, the PET is calculated for the maximum daily temperature of a hot day with a recurrence time of 3 years in 2050 and 2085. This recurrence period was chosen because it represents a hot summer day, that has a considerable probability of occurring, but is hot enough that it does not occur every year. The return periods of maximum daily temperatures in Rotterdam are calculated for KNMI weather station 344 Rotterdam.

By calculating the heat stress for a hot day with a return period of 3 years, model runs are carried out on days in the current and future climate with the same recurrence time. After comparison, the difference between current and future heat stress is analysed.

This part of the study contains two model runs, one to calculate the PET in the possible climate of 2050 and to calculate the PET in the possible climate of 2085. The output is compared with the output of the model run of same return period in the current climate, which is carried out in the previous model run. Only the temperature is adjusted in this model run, the other meteorological factors are the same as for the current heat stress day. This is done so that only the effect of temperature rise is assessed.

3.3.3 The effect of trees on heat stress

This part of the study aims to analyse the effect trees have on the local PET. Therefore, multiple model runs with different spatial inputs regarding the presence of trees are carried out. Because the effect trees have on the PET is expected to be largest on a local scale, the model run is zoomed in on a neighbourhood in Rotterdam. The neighbourhood is called Rotterdam West. It is aligned to the neighbourhoods Middelland and Nieuwe Westen. The size of the research area is 1 square kilometre. To analyse the effect trees have on the heat stress in Rotterdam, five PET calculations with different tree-scenarios as input are carried out. The five scenarios are: a model run without trees, a model run with the current number of trees in Rotterdam, a model run where the number of public trees is increased with 10%, a model run where the number of public trees is increased with 30% and a model run where the number of public trees is increased with 50%. For the first model run, all trees are removed from the model and the PET is calculated for the research area without trees.

The urban area of Rotterdam contains over 700 different species of trees. Because of this, a standardized deciduous tree type is added to the model. This standard tree type has a Bowen ratio of 0.4 (-) and a foliage crown factor of 0.75 (-). The height of the trees is twelve meters. This standard tree type is based on the average tree that occurs in the urban environment in the Netherlands. The process of adding trees directly in Tygron is suited for small scale projects. Due to the relatively large scale of this project, trees are added into Tygron as a vector data set containing tree locations created with ArcGIS. The study area naturally contains 2166 trees, most of which are located along streets and in parks (Figure 7).

Figure 7: Locations of trees in study area Rotterdam West. (Scale 1:20,000) (BGT; ESRI)

The additional trees are inserted to the model only on locations considered suited for tree placement. Locations that are suited for tree placement in this study is based on the land use classes of a land-use dataset, the BGT. The land-use classes in which trees occur in the BGT, are recognized as areas suited for tree placement. The land-use classes that contain trees can be seen in Table 5. Figure 8 shows the location of the suited land-use classes in Rotterdam West.

Land use classes suitable for tree placement (BGT)
vegetated land, verge, verge vegetation, building land, dune, mixed forest, grave, grass, grassland, agricultural grassland, remaining grassland, trench, greenery, hedge, semi-paved, unpaved, car parking, shrubs, ditch, unbuilt land, unvegetated terrain section, horse-riding path, pedestrian area, pedestrian path, sand

Table 5: Land use classes in the BGT that contain trees.

Figure 8: Area suitable for tree placement in Rotterdam West. Highlighted area is the area suited for tree placement. (1:20,000)

After selecting the area that is suited for tree placement, random tree locations are generated in this area with ArcGIS. These tree locations are added to Tygron as a so-called future measure. Tygron can recognize these point locations as standard deciduous trees. After inserting these additional trees to the data set, the PET can be calculated with the new spatial information.

To study the effect of trees on heat stress, the same climatological input for the day with a return period of 3 years in the current climate as well as the future climates of 2050 and 2085 will be used (Table 6).

Tree scenario	Number of trees	Climate (WH-scenario)	Model run
No trees (0% of original trees)	0	Current (2022)	3.1.1
		2050	3.1.2
		2085	3.1.3
Original trees (100% of original trees)	2166	Current (2022)	3.2.1
		2050	3.2.2
		2085	3.2.3
A few additional trees (110% of original trees)	2383	Current (2022)	3.3.1
		2050	3.3.2
		2085	3.3.3
Some additional trees (130% of original trees)	2816	Current (2022)	3.4.1
		2050	3.4.2
		2085	3.4.3
Many additional trees (150% of original trees)	3249	Current (2022)	3.5.1
		2050	3.5.2
		2085	3.5.3

Table 6: Model runs for the assessment of the effect of trees on heat stress in Rotterdam.

4 Results

4.1 Current heat stress in Rotterdam

4.1.1 Summer days and return periods

The current heat stress in Rotterdam is evaluated by means of a model run using the DPRA Heat Module from the Tygron Geodesign Platform. The model output of the current heat stress in Rotterdam is shown here, together with the results of the return period calculations of the KNMI data. The different maximum daily temperatures that have occurred in Rotterdam all have a different return period (RP). The maximum daily temperatures, together with the other climatological data of the reference days on which the temperatures took place is used to determine the PET (Table 7). The first day has the longest return period and maximum daily temperature, with 33 years (RP 33). The other reference days that are used to calculate the PET have a return period of 5,5 (RP 5.5) and 3 years (RP 3). To be able to quantify what maximum temperatures can be expected to occur or be exceeded every summer, the PET on a summer day with a return period of 1 year is calculated (RP 1).

Model run	**Return Period (years)**	**Reference day**	**Maximum daily temperature (°C)**	**Hour of day with maximum temperature**	**Wind direction (degrees, 90E, 180S, 270W, 360N)**
1.1	33	2022/07/19	37.1	15:00	123
1.2	5,5	2018/08/07	34.4	15:00	202
1.3	3	1994/07/24	33.1	16:00	93
1.4	1	2001/07/05	31.7	15:00	109

Table 7: Climate data of reference days used in model run for the calculation of current heat stress.

4.1.2 The spatial distribution of PET in the current climate

On a summer day with a return period of 33 years, the maximum calculated PET in the study area is 50 °C. The average PET in the study area for this model run is 46.7 °C. As can be seen, in most of the area a PET higher than 41 °C can be experienced, which corresponds to extreme heat stress (Figure 9). Transitions between higher PET values (red areas) of 49 °C or higher and lower PET values (yellow areas) of about 41 °C on this map are often abrupt, especially in built-up areas. In some open areas, the transitions between higher and lower PET values are smoother, as can be seen in Kralingse Bos, in the northeast of the study area and open spaces in the southwest and near the Meuse in the east of the study area. Around trees and at some sides of buildings, the PET is lower compared to the surrounding area (Figure 10).

The average PET on the summer day with a return period of 5 years varies greatly throughout the study area (Figure 11). The average PET in the study area is 43.7 °C. In parks and open spaces, a lower PET (green areas) of about 33 - 37 °C , is shown compared to other parts of the study area, such as streets or roads, that are of higher PET values (red or orange), of 45 °C or higher. In some areas, a higher PET can be experienced than in others, regardless of if the areas are open spaces, built-up areas or streets. The centre of the city appears to have a higher PET than the South of the city (Figure 11). The least variation in PET can be found in the South-East of the study area. In areas with small streets, where trees are located, variation in PET is calculated. This is the case for the largest part of the study area. Similar to the PET map of the summer day with a return period of 33 years, the PET is lower near trees and at some sides of buildings (Figure 12). Warmer areas seem to appear further away from obstacles such as trees or buildings.

The average PET in the study area on a summer day with a return period of 3 years is 41.2 °C. The most severe heat stress, with a PET of 49 °C or higher, can be found mostly in the center of the city, at or close to blocks of buildings and in streets (Figure 13). In most open spaces, areas with lower PET can be found. Especially in parks and along the centre of the city, PET values between 33 to 37 °C can be experienced. In most of the study area, relatively warm (red) and cool (green) areas alternate. This means that locations with severe heat stress do not show smooth transitions from locations with lower PET. Less variation can be found in the south-west of the study area as well as around Kralingse Bos in the northeast of the area. The pattern of lower PET values near trees can also be found on the summer day with a return period of 3 years (Figure 14). Overall, closer to buildings, lower PET values can be seen as well.

The average PET over the surface area on a summer day with a return period of one year is 40.2 °C. In RP1, the difference between the densely built city centre and the surrounding areas with fewer buildings can be seen most clearly of all model runs (Figure 15). The red areas, indicating severe heat stress, are mostly found in areas with small streets and many building blocks. It is also at these locations where green areas can be found, where mild heat stress occurs. Less variation occurs in the surroundings of the city centre, because building blocks are not located as close to each other as in the centre of the research area. However, these are not necessarily the areas with the lowest heat stress. Large areas with a PET of 41 °C can be found here. In the areas with more variation, such as Oude Westen, higher PETs as well as lower PETs can be found. Compared to the other model runs, this is the model run with the most green and the least red areas. In this model run lower PET values can be found near vegetation and buildings as well (Figure 16). However, similar to the other model runs, not on every side of buildings lower PET values can be found. In the square at the top of the image, slightly lower PET values can be found as well. This area of lower PET is not as low as the area near trees and has a very smooth transition from higher to lower PET values, instead of the rather abrupt transition near trees and buildings.

Figure 9: PET in Rotterdam on a hot summer day with a return period of 33 years. Model run 1.1 (Scale 1:100,000)

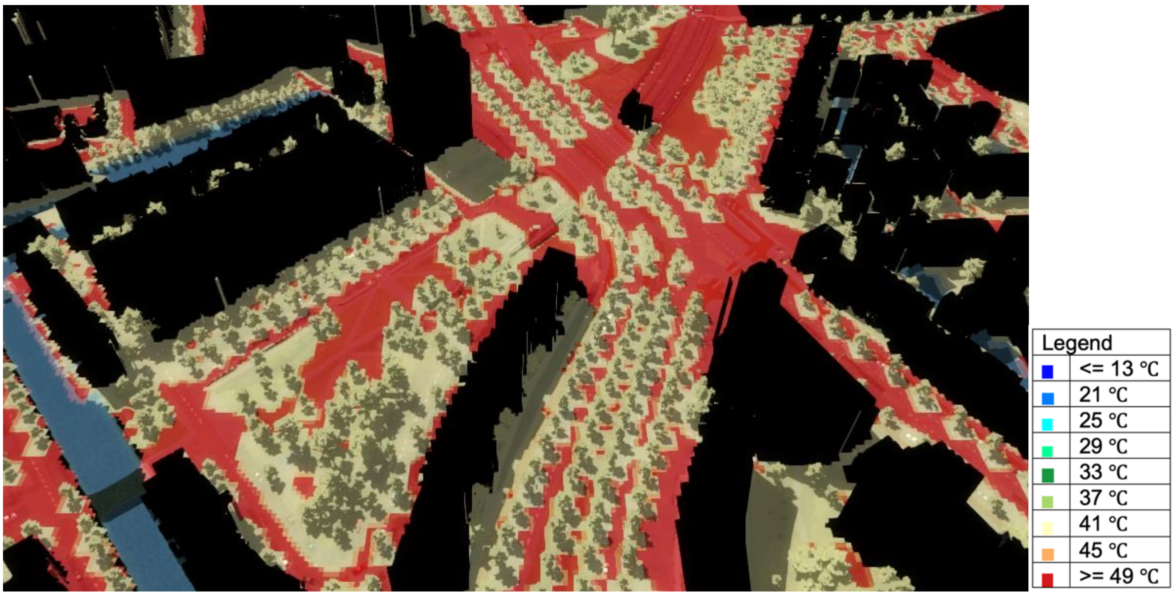

Figure 10: PET in Kralingen, Rotterdam on a hot summer day with a return period of 33 years. Model run 1.1 (Scale 1:1,500)

Figure 11: PET in Rotterdam on a hot summer day with a return period of 5.5 years. Model run 1.2 (Scale 1:100,000)

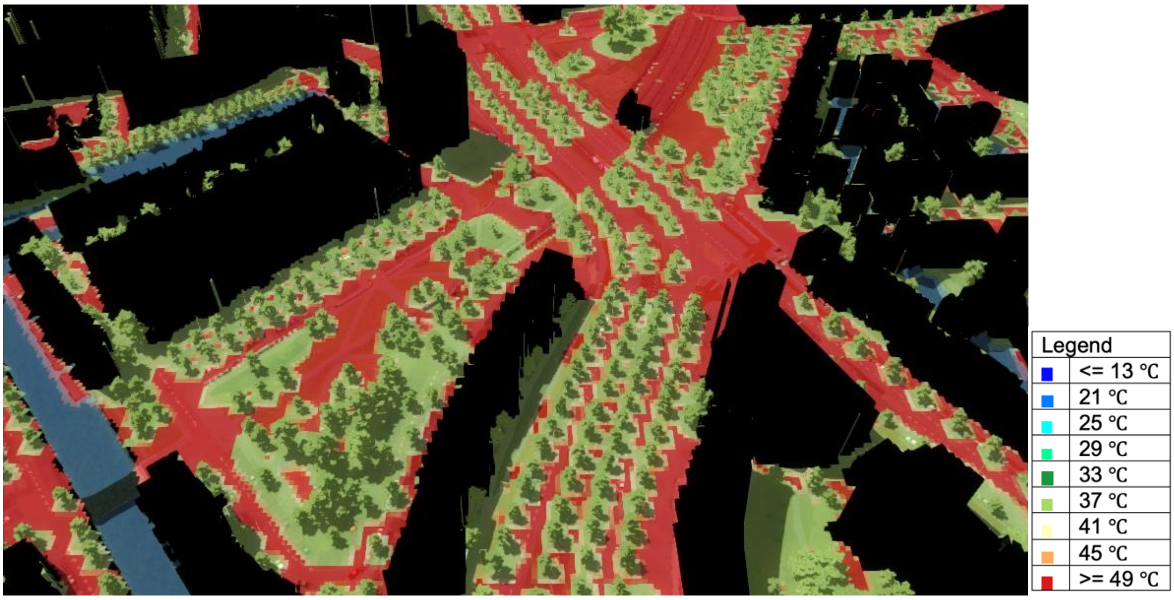

Figure 12: PET in Kralingen, Rotterdam on a hot summer day with a return period of 5.5 years. Model run 1.2 (Scale 1:1,500)

Legend
<= 13 °C
21 °C
25 °C
29 °C
33 °C
37 °C
41 °C
45 °C
>= 49 °C

Figure 13: PET in Rotterdam on a hot summer day with a maximum daily temperature with a return period of 3 years. Model run 1.3 (Scale 1:100,000)

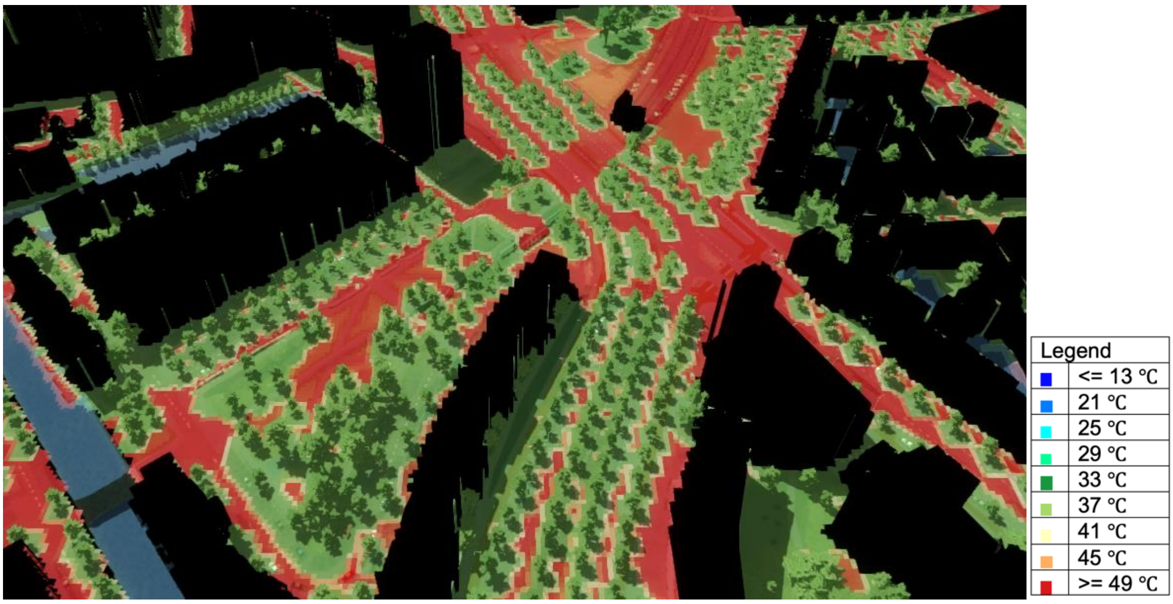

Figure 14: Figure 15: PET in Kralingen, Rotterdam on a hot summer day with a maximum daily temperature with a return period of 3 years. Model run 1.3 (Scale 1:1,500)

Figure 16: PET in Rotterdam on a summer day with a maximum daily temperature with a return period of 1 year. Model run 1.4 (Scale 1:100,000)

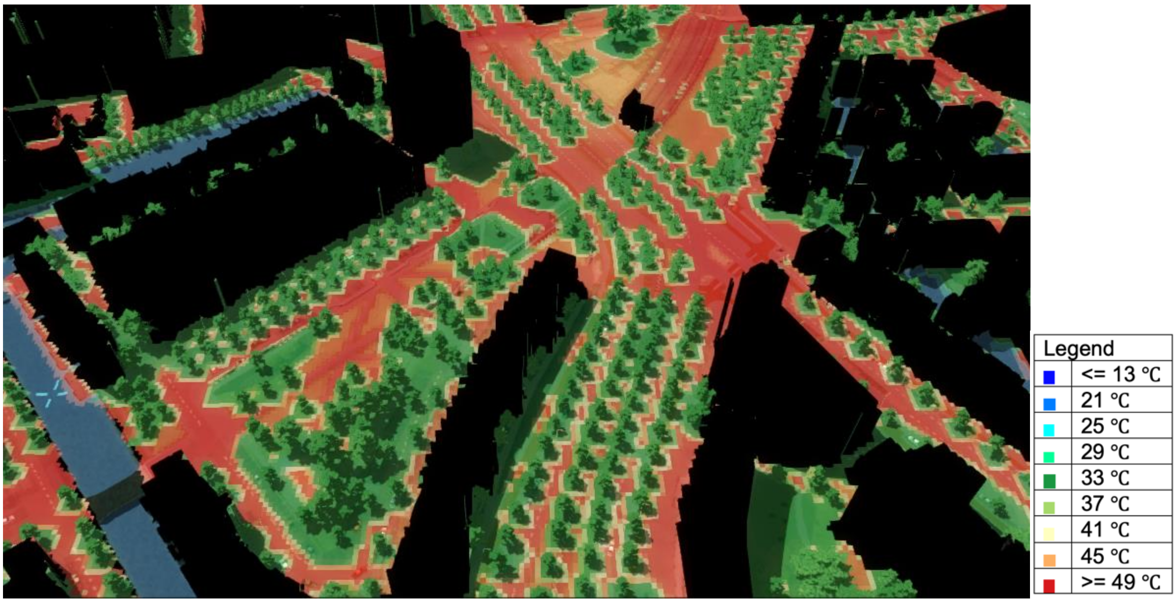

Figure 17: PET in Kralingen, Rotterdam on a summer day with a maximum daily temperature with a return period of 1 year. Model run 1.4 (Scale 1:1,500)

No surface area has a PET lower than 35 °C for the summer day with a return period of 33 years, and on the summer day with the return period of 5 years, only 1% of the study area is in this range (Figure 18). The largest area that falls within this range is in the model run of the summer day with a return period of 1 year, which has the coolest atmospheric temperature of all four return periods. Connections between the atmospheric temperature of the simulated summer day and part of the surface area in the lowest and highest PET ranges are shown. To illustrate, on the summer day with the lowest atmospheric temperature, which has a return period of 1 year, the largest part of the study area is 35°C or lower, compared to the surface area in that range of the other return periods. On the summer day with the highest atmospheric temperature, the return period of 33 years, the smallest part of the study area is 35°C or lower, compared to the surface area in that range of the other return periods. This is the same but in reverse for the part of the surface area that is 45°C or higher. In this range, the largest part of the surface area is covered on the summer day with the lowest atmospheric temperature. This relationship between the part of the surface area and PET range cannot be seen in the ranges of 35-41°C and 41-45°C. A relatively warmer atmospheric air temperature does not necessarily show a relatively larger or part of the surface area in the 35-41°C, and a relatively lower air temperature does not show a relatively larger part of the surface area in the PET range of 41-45°C, compared to the other model outputs. For the summer day with a return period of 33 years, the largest part of the study area is in >45 °C (Figure 18). For the summer day with a return period of 5.5 years, this is also the case, but for the return period of 1 and 3 years, the largest part of the area shifts to 41-45°C. The exact percentages of the surface areas can be found in Table 14 in Appendix I.

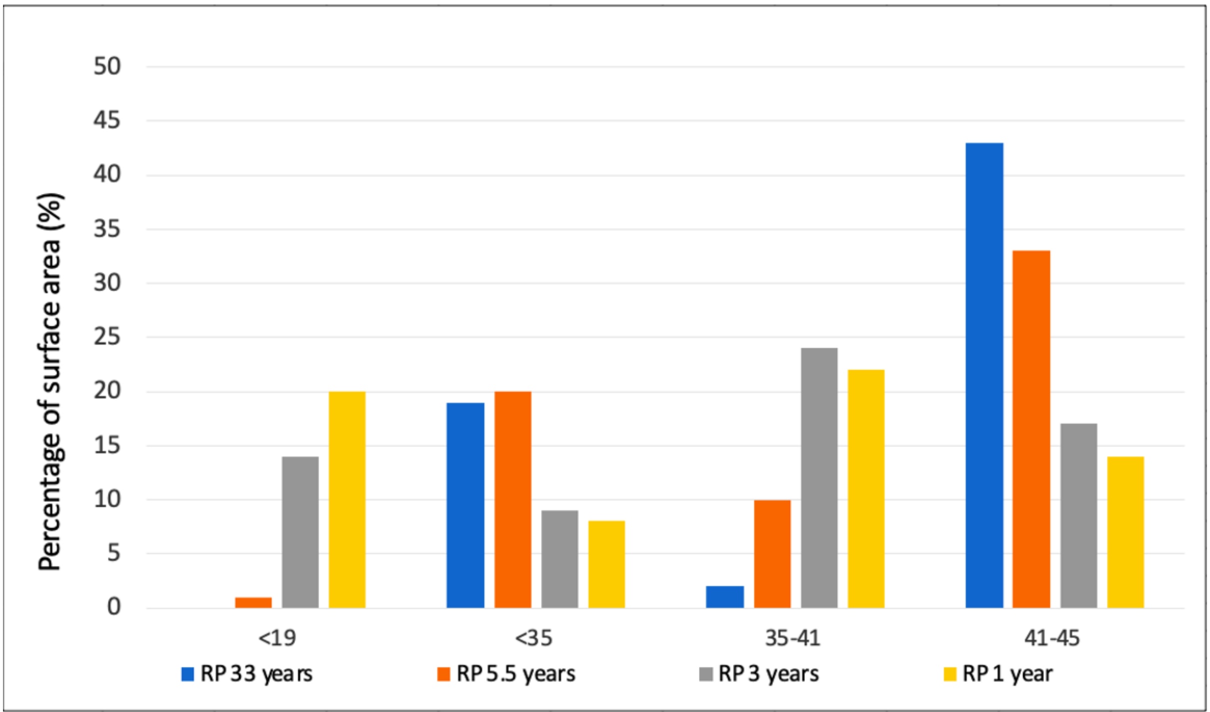

Figure 18: Percentage of surface area in the research area within certain PET-classes. RP is 'return period', RP 33 years refers to the model run where the PET on a summer day with a return period of 33 years is calculated.

4.1.3 The pattern of PET in the current climate

The pattern of the PET is different between the summer day with a return period of 33 years and the summer day with the return period of 1 year, at some locations the change is small and for certain locations the difference is larger (Figure 19). The difference between the patterns of the PET of the two model runs is determined by dividing the PET map of the return period of 33 years with the PET map of the return period of 1 year (Section 3.3.1). Most red areas, which indicate that there is no difference between the PET values of the return period of 33 years and 1 year, map are buildings, because the PET is not calculated for these locations, therefore there is no change between the PET values. The pattern differs especially near trees and at the edges of varying patterns (Figure 20). Small spots of other colours near trees indicate that the PET varies for small locations.

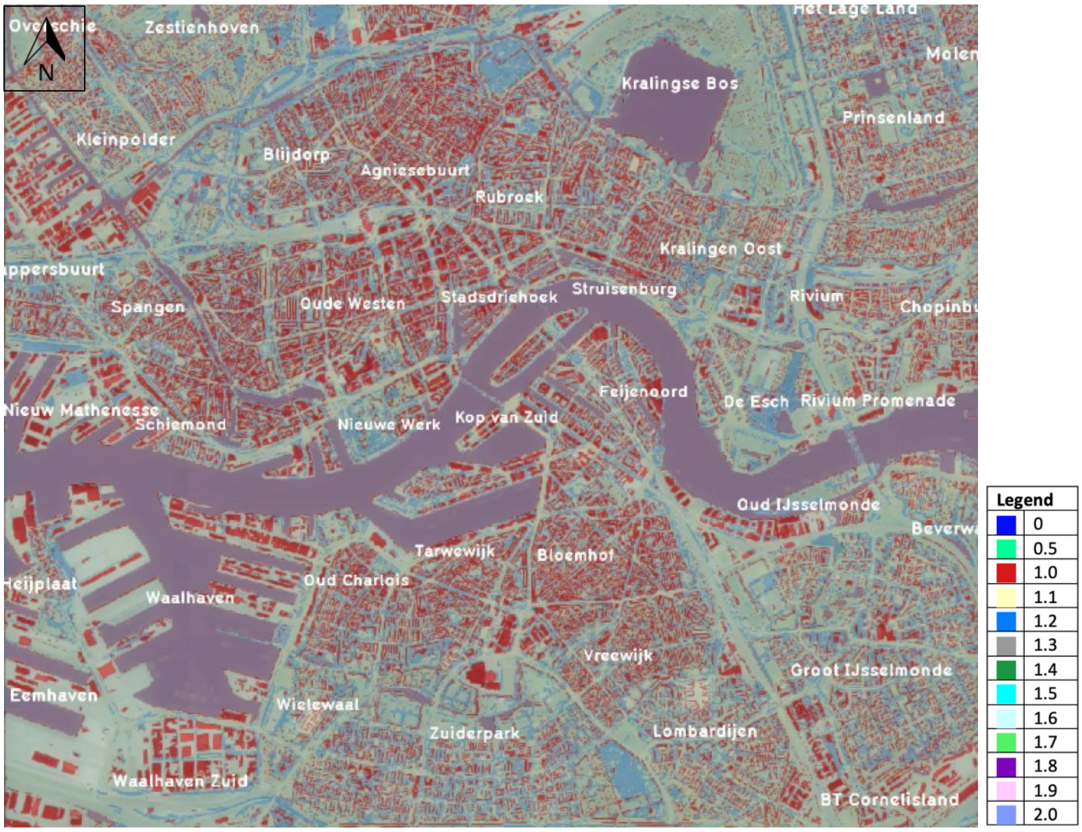

Figure 19: Change in the spatial pattern of the PET between PET calculation on summer day with a return period of 33 years and 1 year in Rotterdam. (Scale 1:100,000)

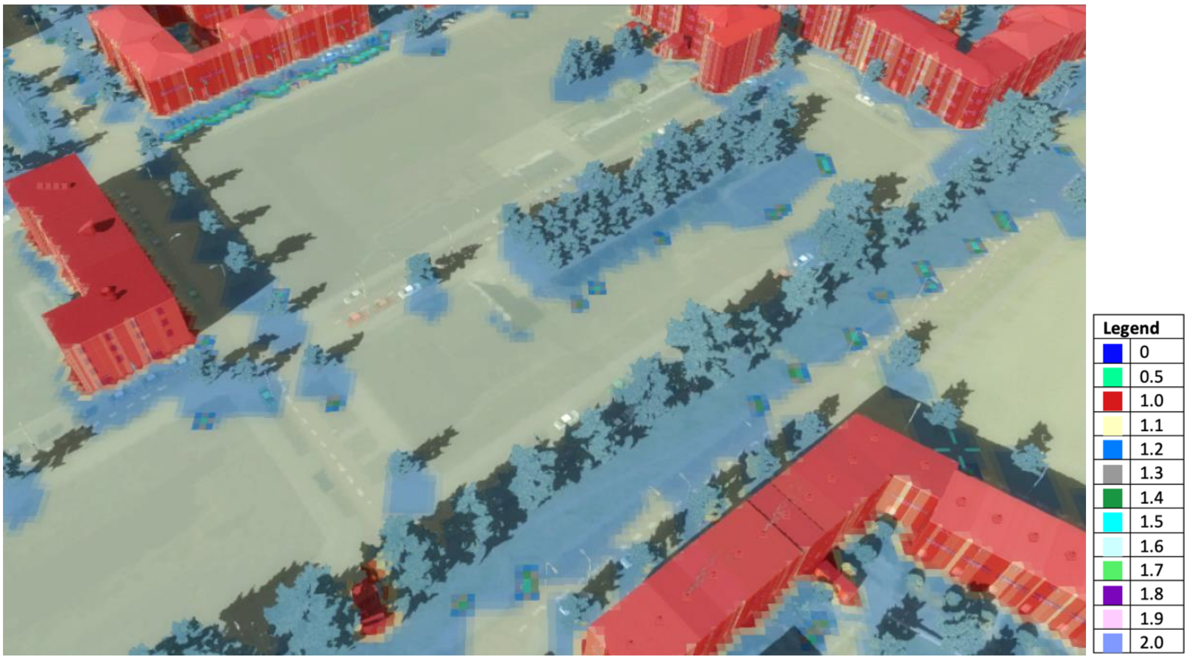

Figure 20: Change in the spatial pattern of the PET between PET calculation on summer day with a return period of 33 years and 1 year in Kralingen, Rotterdam. (Scale 1:500)

The effect of wind is calculated with changes in wind direction. To assess the effect of wind on heat stress, the wind direction for a summer day that occur every 5.5 years is edited. The wind direction of the reference day that has a recurrence time of 5.5 years, August 7th, 2018, is 202 degrees (Table 8). The perpendicular wind directions are 292 and 112 degrees. The opposite wind direction is 22 degrees. The different wind directions and where the wind originates from is presented in Table 8. The PET calculations of the summer day with a recurrence time of 5.5 years with varying wind directions can be found in Appendix I. Variation between the four maps cannot be distinguished on the scale the maps are created on in this study.

Model run, RP 5.5	**Wind direction (degrees)**	**Wind direction**
A: 1.2.1 (original)	202	NNE
B: 1.2.2	292	SSE
C: 1.2.3	112	NNW
D: 1.2.4	22	SSW

Table 8: Model runs with wind directions.

The percentage of the open accessible surface area within certain PET-classes varies for the four model runs. The bars presented in Figure 21 show the difference in the percentage of the surface area that falls in a certain PET class. The difference is given compared to model run A (1.2.1), which is the original wind direction. The variation in the percentage of the surface area is largest in the two highest PET classes, for model runs B and C. The difference between model runs A and D is very small, when looking just at percentages of the surface areas. The model run that deviates the most in terms of percentages compared to the original is model run

B, which has a wind direction perpendicular to the original model run. The model run that deviates the most after that is model run C, which also has a wind direction perpendicular to the original wind direction of model run A, however in opposite direction of model run B. Model run D, which has an opposite wind direction to the original model run (A), deviates the least in percentages of surface area within certain PET classes.

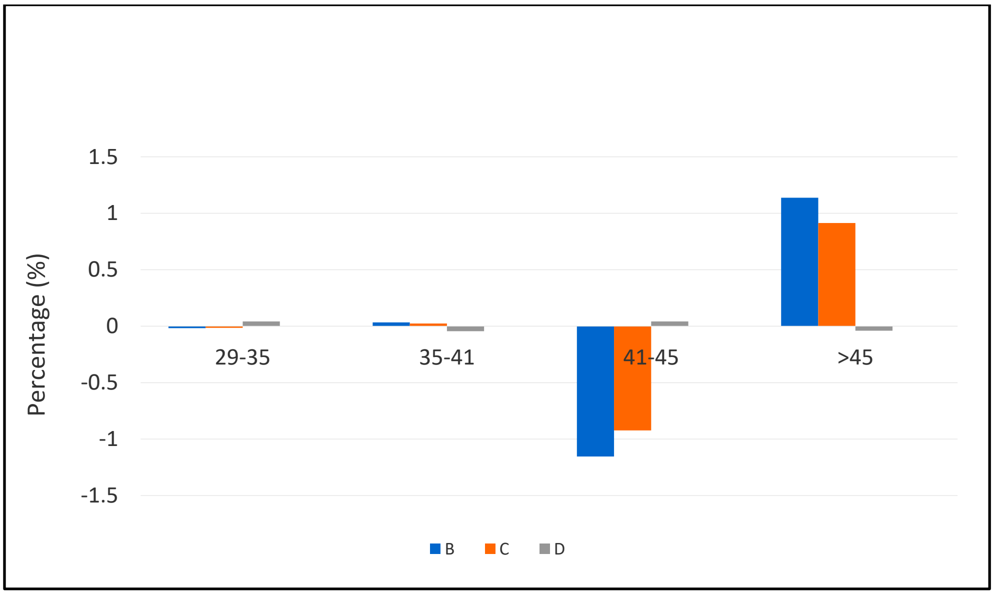

Figure 21: Difference in part of the surface area in certain PET ranges of model runs B, C and D, compared to the composition of model run A. A, B, C and D correspond to the model runs in Table 9.

4.1.3 Cool places, shade and average PET near buildings

As described in Chapter 3, climate adaptive cities require cool places within them where civilians can search for shelter from extreme heat stress. In this study, a distinguishment is made between cool places and cool areas. Cool places are outside areas that are open and accessible for all citizens, and require specific elements such as benches, where people can rest on. The cool places are at least 200 m^2 of continuous shade and PET below 38°C. Cool areas are all shaded areas where the temperature is below 38°C, that are eligible to qualify as cool places. Whether the areas also meet the other guidelines an official cool place should meet, is not assessed in this study.

The size of the area that is considered cool in the study area is very similar for the summer days with lower return periods of 5.5, 3 and 1 year (Table 8). Differences are hard to distinguish between the cool areas of the summer days with the lower return periods (Figure 23). On the summer day with a higher return period, the cool area is almost ten times smaller. The cool areas of the summer days with the lower return periods area very similar in size and in where in Rotterdam they are located. However, there is a clear difference between areas that are considered cool on a summer day with a return period of 33 years and the area that is considered cool on days with lower return periods (Figure 23). The areas that are always cool (red) are the areas that are cool on the summer day with a return period of 33 years as well as the other summer days. The green areas are the locations where cool area only occurs on the summer days with lower return periods, of 1, 3 and 5.5 years.

The cool areas that are present on the summer day with a return period of 33 years seem to occur randomly throughout the study area. They can be found in the docks at the Waalhaven, in the southeast, in built-up areas in the north and south of the study area, and a few can be seen in open areas such as parks of squares. For the summer day with a return period of 1, 3 or 5.5 years, cool areas appear throughout the entire study area (Figure 22). Street-like patterns can be distinguished, but also large shapes which could indicate cool places in parks are visible. The pattern of the locations of cool areas is similar on the summer day with a return period of 3 years. On the summer day with a return period of 1 year, the cool areas spread throughout the study area, showing no clear relations between built-up areas or open spaces.

No clear spatial relation between the presence of cool areas and water can be distinguished on any of the four summer days (Figure 23). The total part of the open accessible surface area that is considered cool is largest on the summer day with a return period of 1 year (Table 8). However, the cool area on the summer day with a return period of 3 years is smaller than the cool area on the summer day with a return period of 5.5 years.

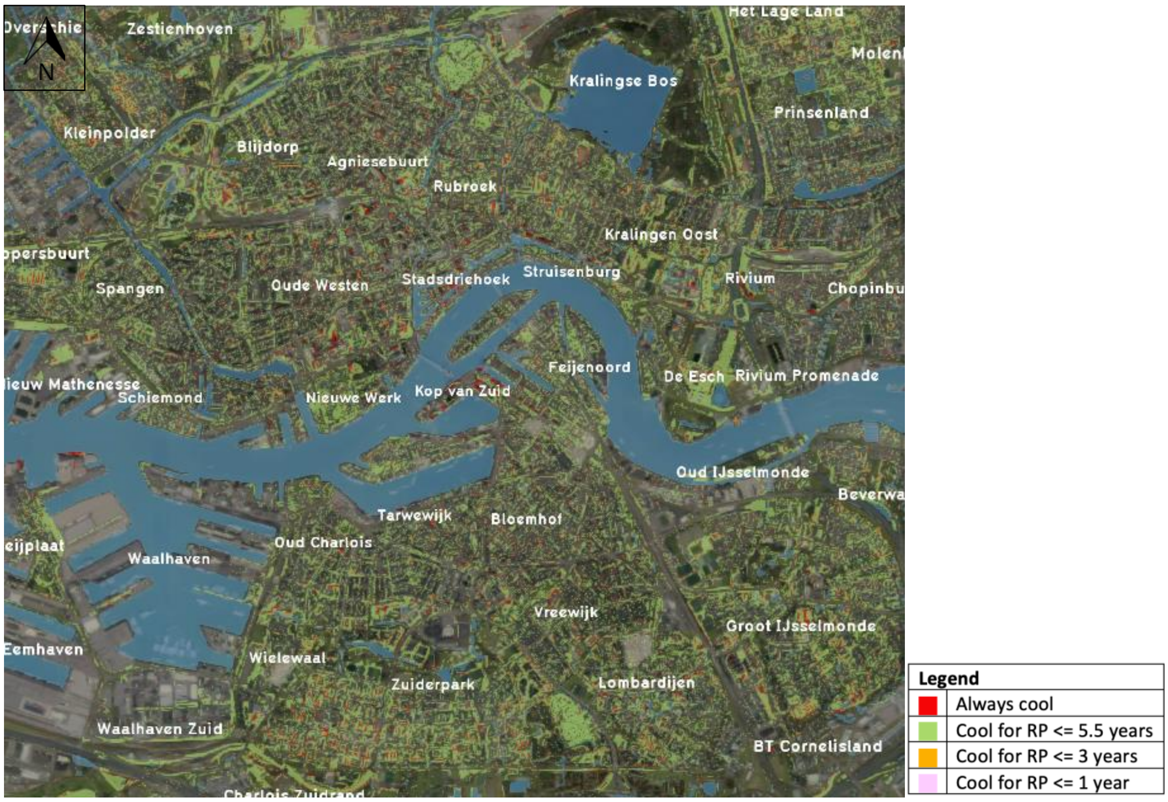

Figure 22: Cool areas in Rotterdam for the summer days with return periods (RP) of 33 years, 5.5 years, 3 years and 1 year. (Scale 1:100,000)

Figure 23: Cool areas in Rotterdam for the summer days with return periods (RP) of 33 years, 5.5 years, 3 years and 1 year. (Scale 1:1000)

Model run (RP or year)	Cool areas (m^2)	Part of open space
RP 33 years (current climate)	2.35 x 10^5	4.9%
RP 5.5 years (current climate)	2.10 x 10^6	44.6%
RP 3 years (current climate)	2.07 x 10^6	44.6%
RP 1 year (current climate)	2.10 x 10^6	43.9%

Table 9: The size of the cool areas of each of the summer days in square meters and percentage of the open accessible surface in the study area. RP stands for return period.

With the spatial input used in this model run, the total part of the total open accessible surface area that is shaded during the highest solar position is 45.2% (Figure 24). This excludes buildings and water bodies. The part of the walking routes that is shaded during the highest solar position is 38.8%. The calculations of shade only take the open accessible surface area into account, therefore water and buildings are not considered shaded or not shaded. Shaded areas can be found at certain sides of buildings and around trees. As a result of this, pedestrian areas that have trees located on or near them are more shaded than others. Also, sometimes footpaths are shaded because they are located in the shade from a building. Footpaths that are on the sunny sides of buildings are not shaded at all, expect when there are trees located on or near the walking routes (Figure 25).

Figure 24: Shaded areas in current climate and spatial conditions in Rotterdam, the Netherlands for June 21st at 14:00. Darker areas are shaded and lighter areas are not shaded. (Scale 1:100,000)

Figure 25: Shaded areas in current climate and spatial conditions in Kralingen, Rotterdam, the Netherlands for June 21st at 14:00. Darker areas are shaded, and lighter areas are not shaded. (Scale 1:1,500)

For all summer days the average PET increases when distance from a building increases (Figure 26). The rate at which the PET rises with distance differs for each return period. The PET at certain distances is directly related to the spatial pattern of PET. The fact that the lowest

PET can be found near buildings, indicates that shade provided by buildings causes lower PET values. At larger distances from buildings, the average PET is higher, because at larger distances from buildings streets or squares often can be found. In such areas, few or no structures are present to provide shade and thus lower PET values.

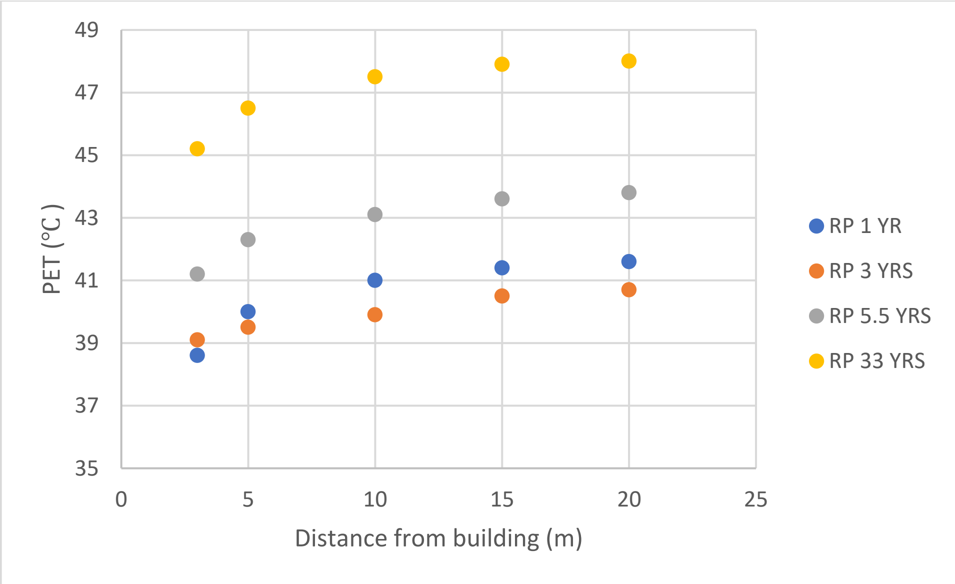

Figure 26: Average PET at distance from buildings for summer days with different return periods. RP stands for return period. For illustration, RP 1 YR is the name for the model run with the summer day with a return period of 1 year.

4.2 Future heat stress in Rotterdam

4.2.1 Atmospheric temperature on summer days in the future

From the transformed climate data of the W_H-scenario in 2050 and 2085 of the KNMI, return periods of the maximum daily temperatures are (Attema et al., 2014). The maximum daily temperatures that have a return period of 3 years for 2050 and 2085 are shown in Table 10. The other climatological input in these model runs is the same as for the model run with the current maximum daily temperature that has a return period in the current climate. The maximum daily temperatures that are expected to be reached or exceeded every 3 years are an estimation, which is entirely based on the results of the temperature data transformation of the W_H-climate scenario of the KNMI'14 report (KNMI, 2014).

Model run	**Year**	**Return period**	**Maximum daily temperature (℃)**
2.1	2050	3 years	36.8
2.2	2085	3 years	38.1

Table 10: Return periods of maximum daily temperatures of transformed KNMI'14 climate data of the WH-scenario for 2050 and 2085.

4.2.2 Spatial pattern of PET in the future climate

The average PET in the study area on a summer day with a return period of 3 years in the forecasted climate of 2050 run is 46.1 °C (Figure 27). The relatively cooler places are highlighted with a very light yellow, indicating a PET of approximately 41 °C. Most areas have a PET between 45 and 49 °C. Darker red areas, which indicate PET above 49 °C, can be found in the study area as well. In parks and larger open areas, smoother transitions from above 49 °C towards 45 °C and 41 °C can be seen. This can be seen most clearly in Kralingse Bos, in the northeast of the study area. In densely built-up areas, abrupter variation between extremely high PETs around 49 °C and less extreme PETs of 41 °C is shown. Overall, most of the study area is coated with a very dark orange, which indicates temperatures between 45 °C and 49 °C or higher. Locations with lower PET values are present near trees and along certain sides of buildings (Figure 28). The transition from higher PET values to lower PET values visible on the zoomed in map is abrupt but shows a slight transition zone of about one grid cell near the edges of the cooler areas around trees.

The maximum PET during a summer day with a return period of 3 years in the forecasted climate of 2085 is 56.6 °C (Figure 29). The lowest calculated PET is 39.8 °C. The average PET in the study area in this model run is 47.9 °C. The first thing that stands out, when comparing this map to the previous map, of the possible PET in 2050, is that this map has a darker red colour where the dark orange areas in the PET map of 2050 are. This indicates that the PET in 2085 can be expected to be even higher than in 2050. Where the PET of 2050 shows smoother transitions in parks and open spaces, the map of 2085 almost only shows abrupt transitions between PET of 41 °C and extremely high PETs of 49 °C or higher. The areas with PETs of 41 °C have the same locations as in the maps shown before. The harbour in the northwest of the area shows extremely high PETs of 49 °C or higher. There is no clear connection between the occurrence of water and low or high PETs visible on this map. The pattern of the PET seems very similar for the forecasted climate of 2085 and 2050. The areas around trees and at certain sides of buildings are cooler compared to the rest of the study area (Figure 30).

Neither the model runs of the forecasted heat stress of the future climate have a surface area where the PET is between 29 and 35 °C. There is a considerable difference between the percentage of the surface area that has a PET between 35 and 41 °C. A large difference between the two model runs is the percentage of surface area where a PET between 41 and 45 °C can be experienced. In 2050, nowhere in the study area PETs that fall within that range can be seen.

Figure 27: Forecasted PET on a hot day with a maximum daily temperature with a return period of 3 years in Rotterdam in 2050 for the W_H-climate change scenario. Model run 2.1 (Scale 1:100,000)

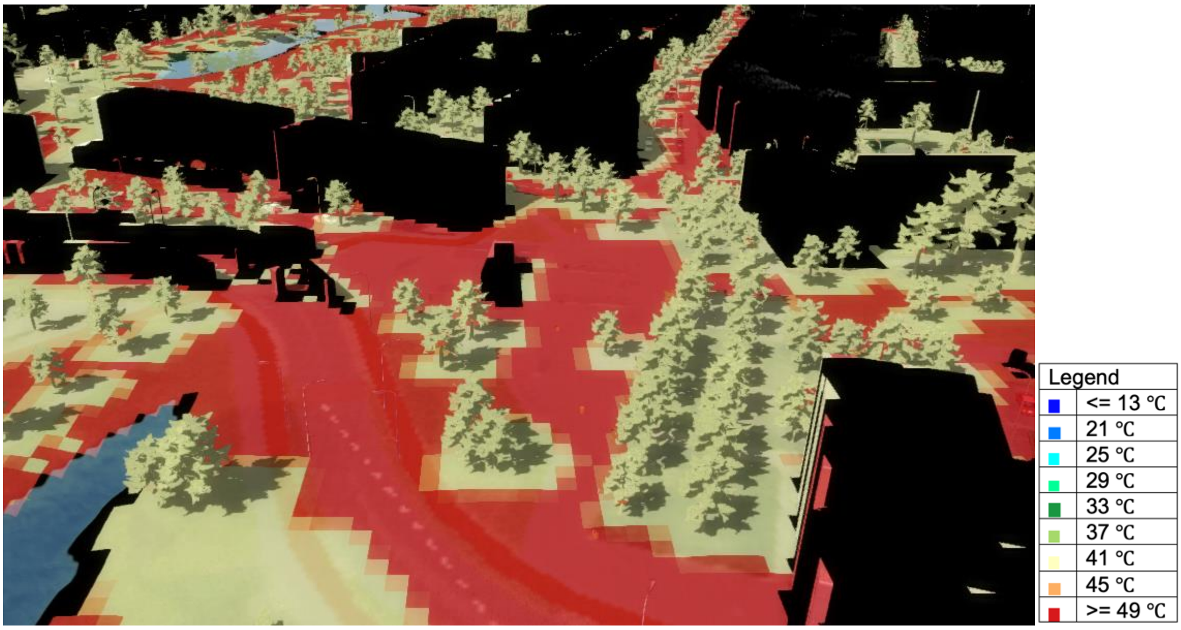

Figure 28 Forecasted PET on a hot day with a maximum daily temperature with a return period of 3 years in Rotterdam in 2050 for the W_H-climate change scenario. Model run 2.1 (Scale 1:1,000)

Figure 29: Forecasted PET on a hot day with a maximum daily temperature with a return period of 3 years in Rotterdam in 2050 for the W_H-climate change scenario. Model run 2.2 (scale 1:100,000)

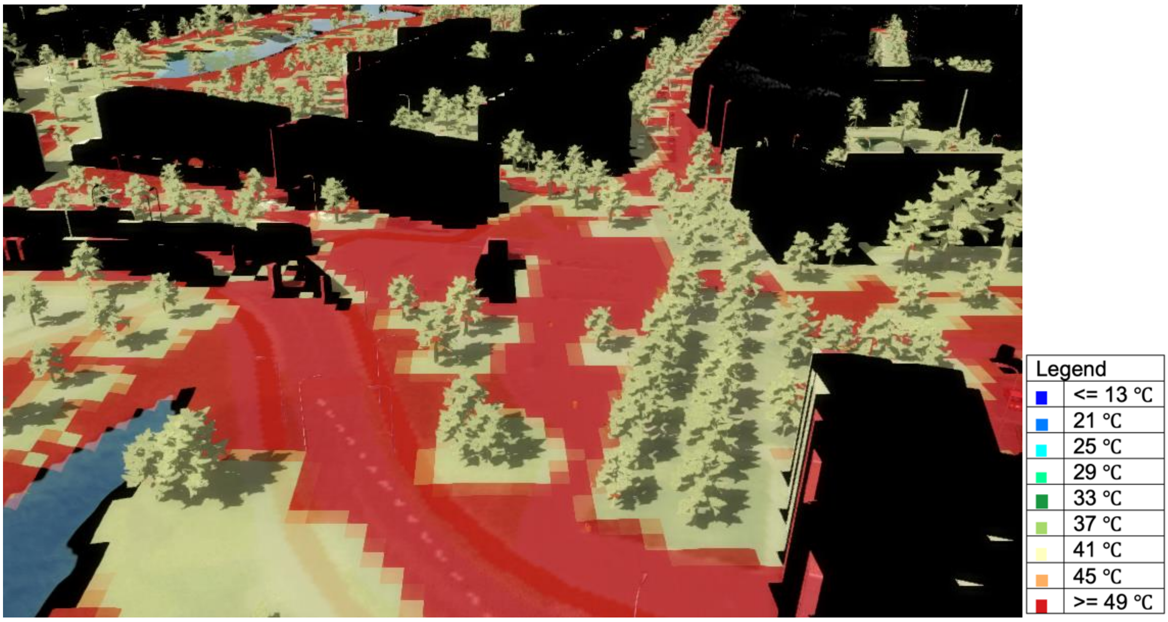

Figure 30 Forecasted PET on a hot day with a maximum daily temperature with a return period of 3 years in Rotterdam in 2050 for the W_H-climate change scenario. Model run 2.2 (Scale 1:1,000)

Model run	**Year**	**(%) PET < 35** ℃	**(%) PET** 35 – **41** ℃	**(%) PET 41 – 45** ℃	**(%) PET >45** ℃
2.1	2050	0	36.2	0	63.8
2.2	2085	0	10.4	25.8	63.9

Table 11: Percentage of the study area within certain PET classes

4.2.3 The pattern of PET over time

The average difference between the PET in the current climate is 4.9 ℃. This difference can be seen over the entire study area, indicated with a dark red colour (Figure 31). In densely built-up areas, more variation in the difference in PET can be found. The difference between the current and future PET tends to be lower in built-up areas. In Kralingse Bos, as well as other open spaces, slightly lower PETs can be seen as well. Nowhere in the study area the future PET of 2050 remains the same or is lower than the PET in the current climate. From a closer point of view, it is clear that the difference in PET between the current climate and the forecasted climate is similar over the entire study area, except for the transitions from open surface area to water or buildings (Figure 32). The areas where the difference in PET is not 4.9 ℃ are one grid cell wide bands along buildings and water. Besides these areas, the difference is equal over the entire study area.

Similar to the difference between the PET of the current climate and the forecasted climate in 2050, the PET is higher in the climate of 2085 than it is in the current climate. The average increase in PET is 6.75 ℃. In built-up areas, more variation in the change in PET can be found (Figure 33). The difference between the current and future PET of 2085 tends to be lower in built-up areas, compared to the rest of the study area. Also, in Kralingse Bos locations with a slightly lower change in PET can be found. The pattern of the difference in the PET between the current climate and the forecasted climate of 2050 is similar to the pattern of the difference in PET between the current climate and the forecasted climate of 2085 (Figure 34). The difference is 6.75℃ in the entire study area, except for the grid cells that align water or buildings, thus adjacent to areas where the PET is not calculated.

On average, the PET is 1.85 ℃ higher in 2085 compared to 2050. This increase seems equal for the entire study area, however, when looking very closely, increase is smaller in densely built-up areas (Figure 35). Because the average increase is already relatively low, considering the maps legend, this cannot be seen very clearly. The pattern of the difference in PET in this scenario is similar to the two other difference maps. Also in this map, the difference is equal for the entire study area, except for the grid cells adjacent to areas where the PET is not calculated (Figure 36).

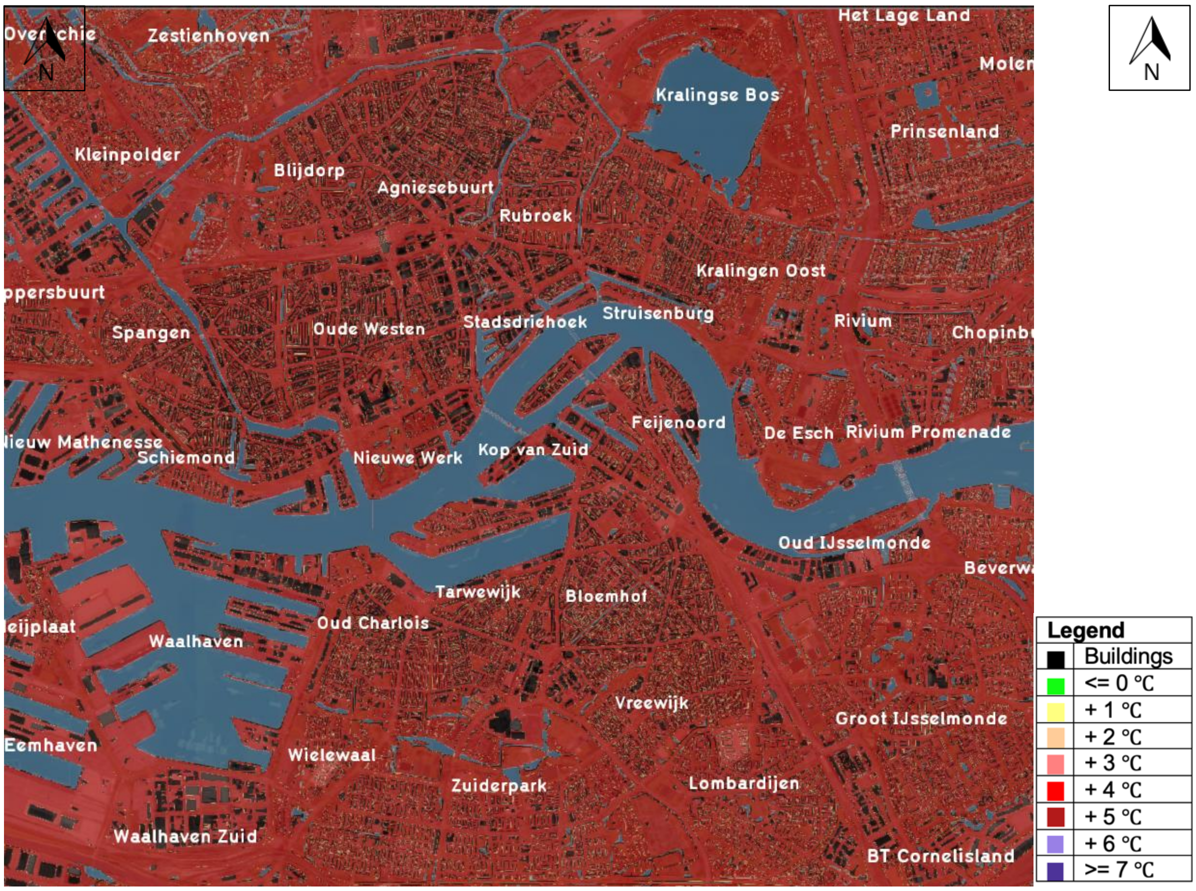

Figure 31: Difference in PET on a summer's day with a return period of three years between the current climate compared to the possible future climate in 2050, considering the W_H-climate change scenario. Model run 1.3 and 2.1 (Scale 1:100,000)

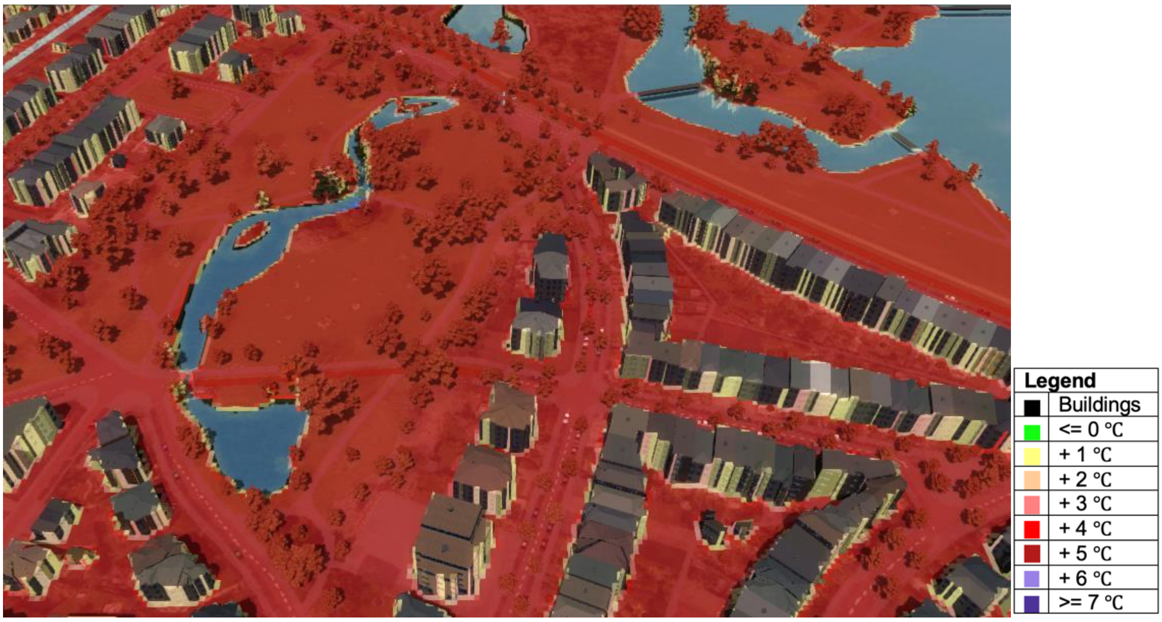

Figure 32: Difference in PET on a summer's day with a return period of three years between the current climate compared to the possible future climate in 2050, considering the W_H-climate change scenario. Model run 1.3 and 2.1 (Scale 1:1,500)

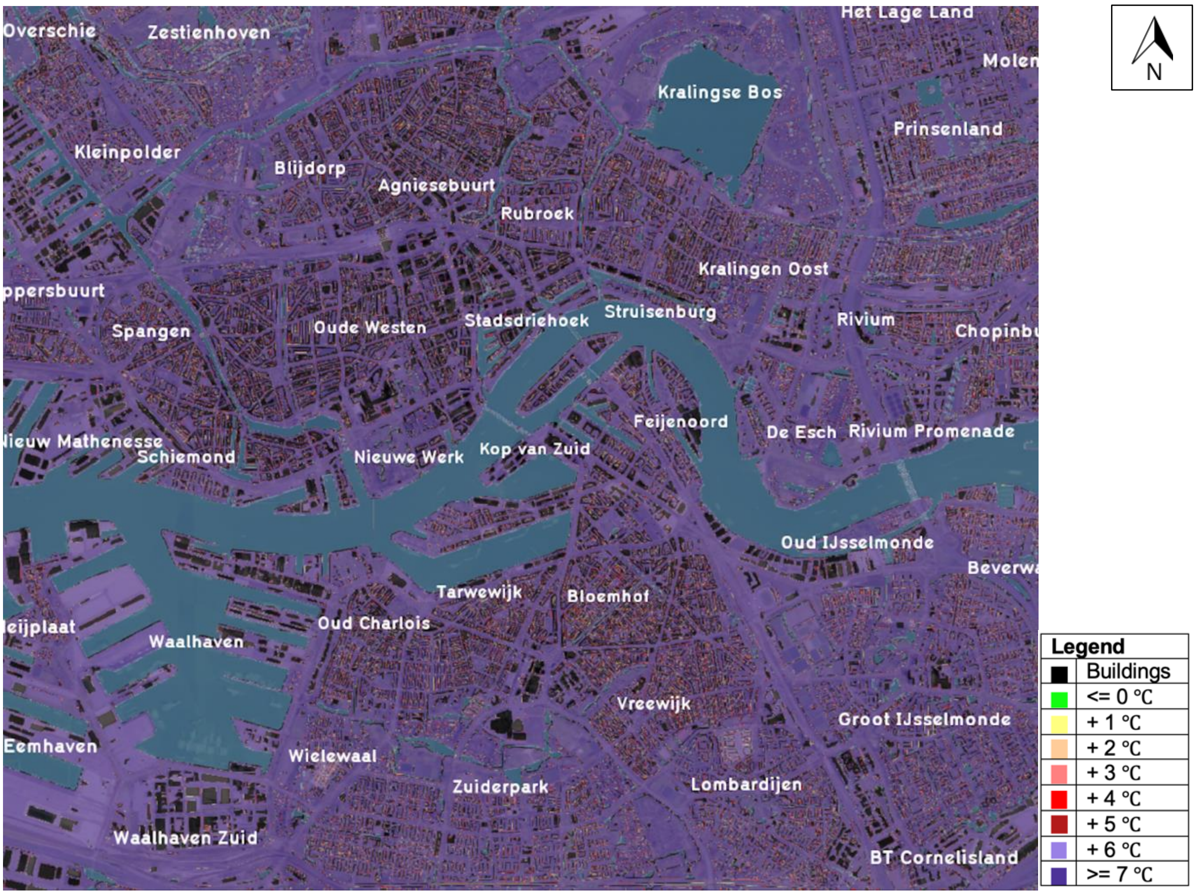

Figure 33: Difference in PET on a summer's day with a return period of three years between the current climate compared to the possible future climate in 2085, considering the W_H-climate change scenario. Model run 1.3 and 2.2 (Scale 1:100,000)

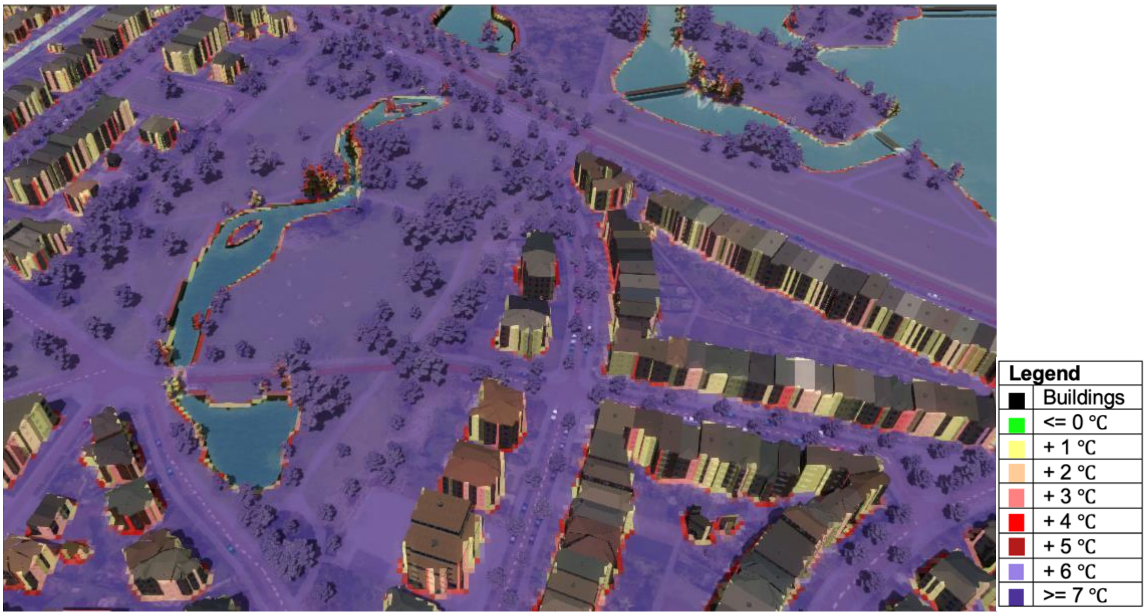

Figure 34: Difference in PET on a summer's day with a return period of three years between the current climate compared to the possible future climate in 2085, considering the W_H-climate change scenario. Model run 1.3 and 2.2 (Scale 1:1,500)

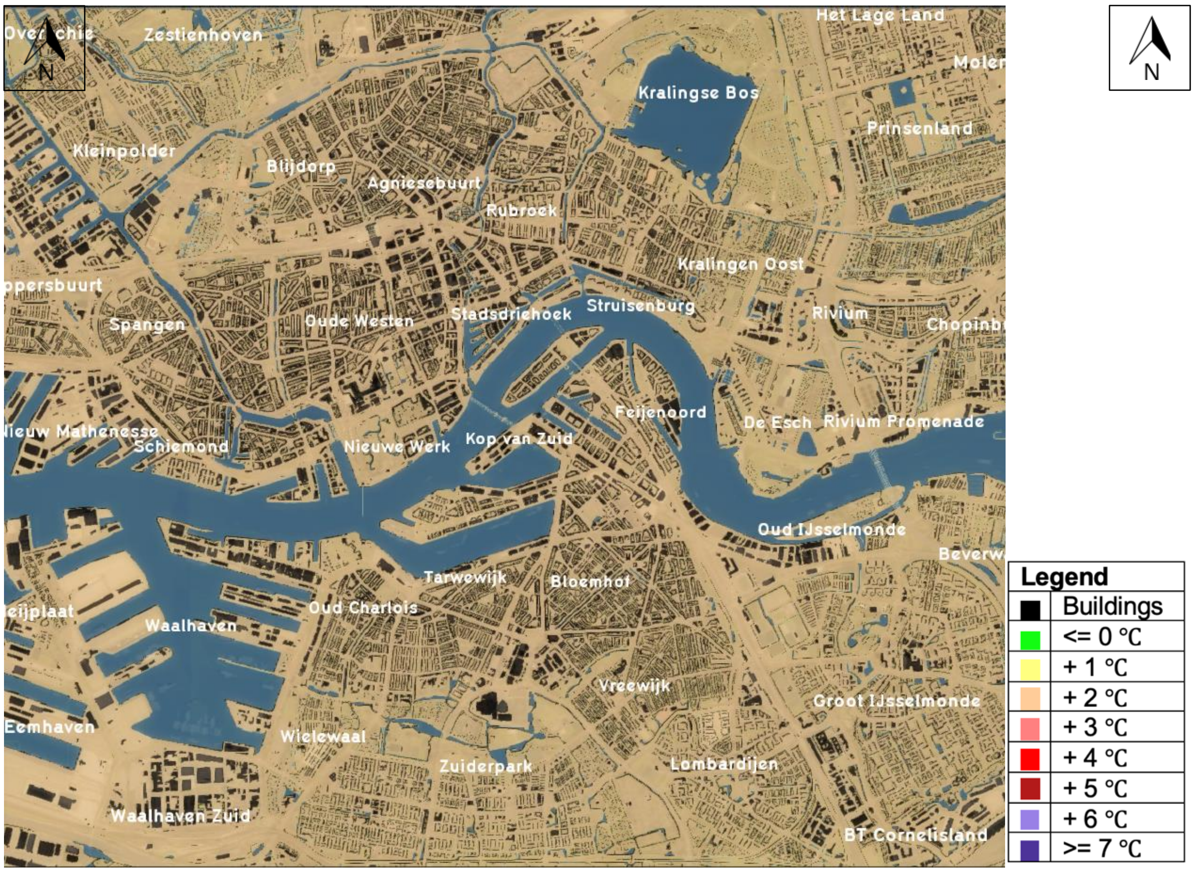

Figure 35: Difference in PET on a summer's day with a return period of three years between the possible future climate in 2050 compared to the possible future climate in 2085, considering the W_H-climate change scenario. Model run 2.1 and 2.2 (Scale 1:100,000)

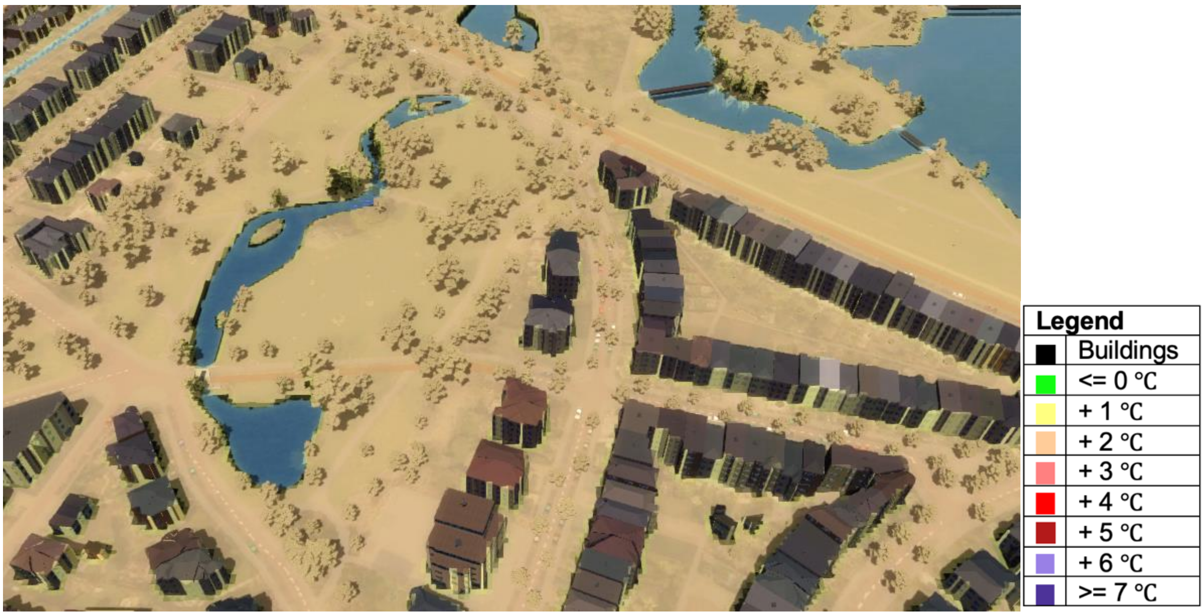

Figure 36: Difference in PET on a summer's day with a return period of three years between the possible future climate in 2050 compared to the possible future climate in 2085, considering the W_H-climate change scenario. Model run 2.1 and 2.2 (Scale 1:1,500)

4.2.3 Cool places, shade and average PET near buildings

In the forecasted climate of 2050 and 2085, the areas that are considered cool cover approximately 5% of the study area (Table 12). The locations of these cool areas do not appear to have a clear connection to other spatial factors, such as buildings, open space or water (Figure 37 and 38).

During this part of the study, only the climatological input was adjusted. Shade is influenced in Tygron by structures such as buildings or vegetation. Therefore, there is no difference in the shade between the model runs from the first part of the study of the current climate, and the model runs of the future climate. The percentage of the open space in the study area that is shaded in the future climate is 45.2% and for walking routes the percentage is 38.8%, at the highest solar position of the year.

Figure 37: Cool areas in the forecasted climate of 2050 in Rotterdam. (Scale 1:100,000)

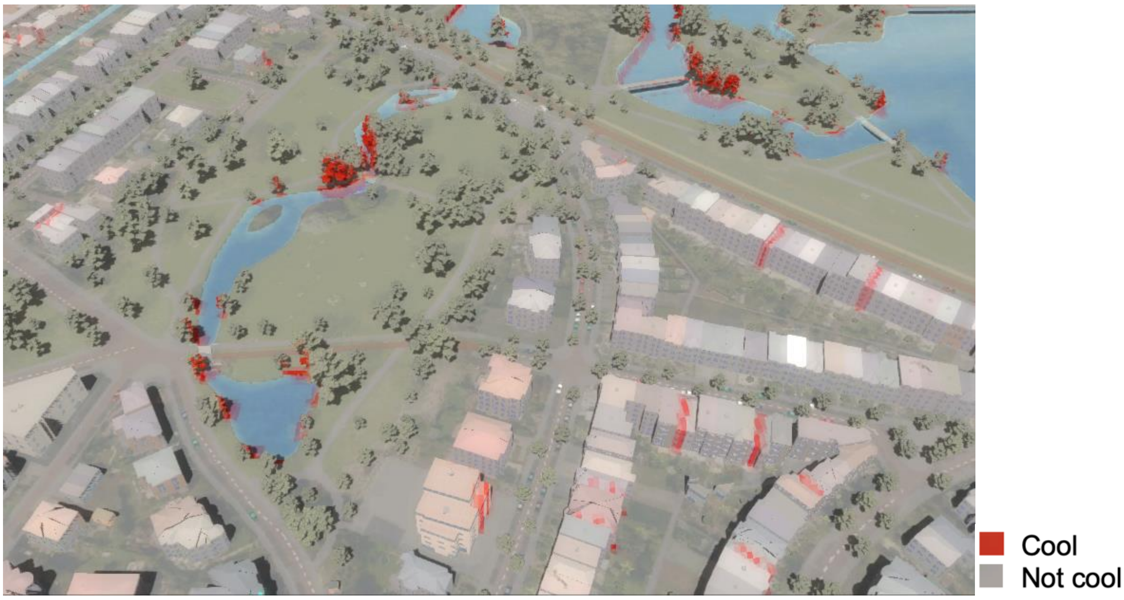

Figure 38: Cool areas in the forecasted climate of 2050 in Rotterdam. (Scale 1:1,500)

Model run (RP or year)	Cool areas (m^2)	Part of open space
RP 3 years (2050)	2.41 x 10^5	5.1%
RP 3 years (2085)	2.35 x 10^5	4.9%

Table 12: The size of the cool areas of each of the summer days in meters and percentage of the open accessible surface in the study area. RP stands for return period.

For each of the three modelled climates, the average PET increases with distance from a building (Figure 39). The rate at which the PET increases is equal for each of the climate scenarios. On average, the highest PET at 3 meters from a building is found in the predicted climate of 2085, which is 45.8 °C. Thereafter a slightly lower PET can be seen in the predicted climate of 2050, which is 44.1 °C. The lowest PET can be found in the current climate, which is 39.1 °C. The increasing PET with distance from buildings is in line with the pattern of the PET in the zoomed in PET maps of 2050 and 2085. The PET is lower near trees and near some sides of buildings (Figure 28 and 30). As trees are often located close to buildings, the PET is expected to increase with distance from buildings.

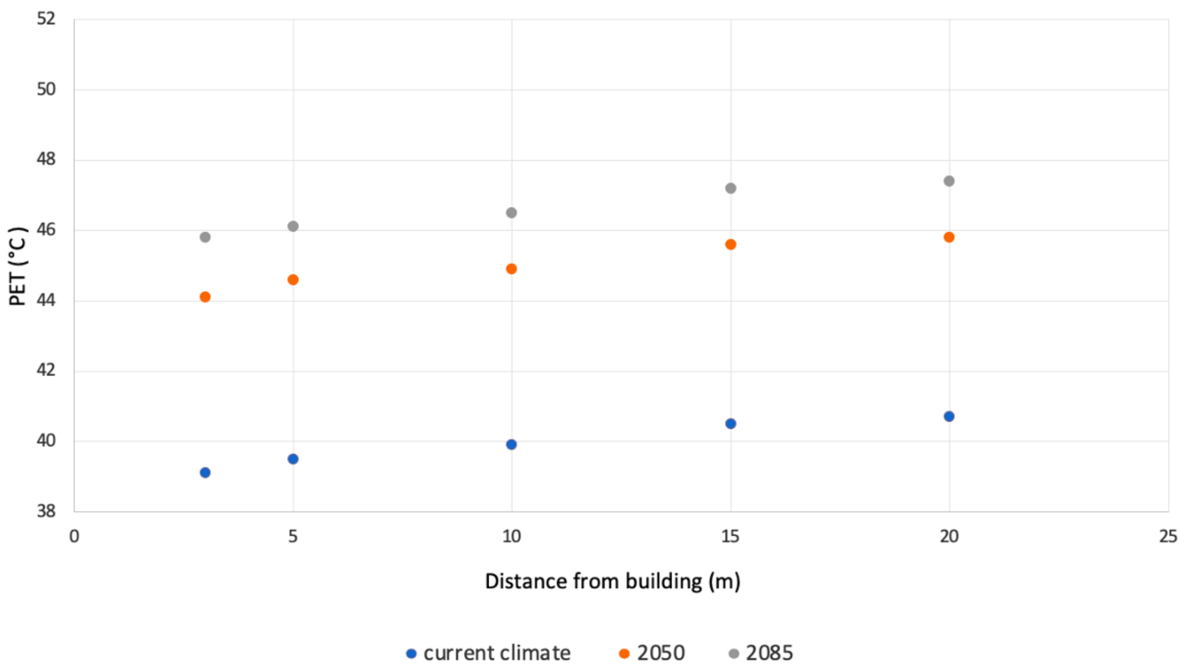

Figure 39: Average PET at distance from buildings.

4.3 The effect of trees on heat stress in Rotterdam

4.3.1 PET and trees

In the scenario without trees, the lowest PET values can be found at the northeast side of buildings (Figure 41). In the model run without trees in the current climate, cooler areas can be found in the open space in the centre at the south of the study area. The PET transitions are very smooth from warmer to cooler near that area. In other climates and at other locations, the transitions from a warm to a cooler PET are abrupt. The average PET is lowest in the current climate and shows more spatial variation there compared to the future climate.

With the original number of trees, colder areas of around 37 °C are modelled northeast of buildings and as spots in streets and in open spaces in the current climate (Figure 42). The spatial orientation of relatively low and high PET values is similar in the current and future PET calculations. In each model run, the transitions from lower PET values (yellow areas) to higher PET (red) appears abrupt.

When the number of trees is increased by 10%, many green areas can be found, indicating a relatively low PET of about 33 °C (Figure 43). The locations with lower PET occur as small spots and as large irregular shapes, that look like groups of spots. In the park west of the water in the centre of the study area, relatively low PETs are calculated. The spatial distribution of higher and lower PET values is equal for each of the three climate scenarios, with a tree number increase of 10%, however the average PET values of the model runs differ.

Most of the open space in the study area is green, indicating a PET of about 33 °C when the number of trees is increased with 30% (Figure 44). The locations of areas with a lower PET are similar for each of the three different climatic situations. The areas with a lower PET are orientated along streets, however not on roads. The park in the centre of the study area is a large area that is cooler than its surroundings. Transitions between PET values of about 33 °C (yellow) and 49 °C or higher (red) are abrupt in each of the three climate scenarios with increase in number of trees of 30%.

When the number of trees in Rotterdam West is increased with 50% in the current climate, most of the area appears green, indicating a relatively low PET of about 33 °C at such locations (Figure 45). In the other two climate situations with a 50% increase in trees, these low values cannot be found, however the maps do indicate similar locations where relatively lower PETs occur. The average PET in the current climate is 39.6 °C, which is the lowest average PET of all of the tree and climate scenarios.

The increase in PET over time according to the forecasted climates of 2050 and 2085 is present in all five tree-scenarios (Figure 46). The difference in PET between the five tree scenarios is largest for the scenario without trees. The lowest PET values appear in the scenario with the most trees, however the lowest PET value in 2050 of this tree-scenario, is still higher than the actual PET in the original tree-scenario in the current climate.

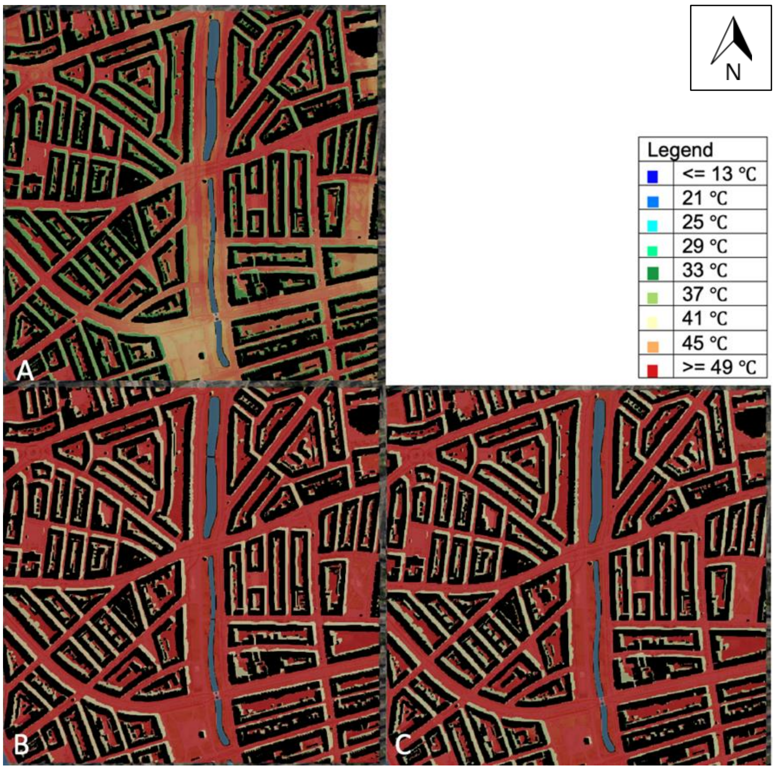

Figure 40: PET in Rotterdam West without trees. The black areas are buildings. Figure A is the PET in the current climate, B in the forecasted climate of 2050 and C in the forecasted climate of 2085. (Scale 1:25,000)

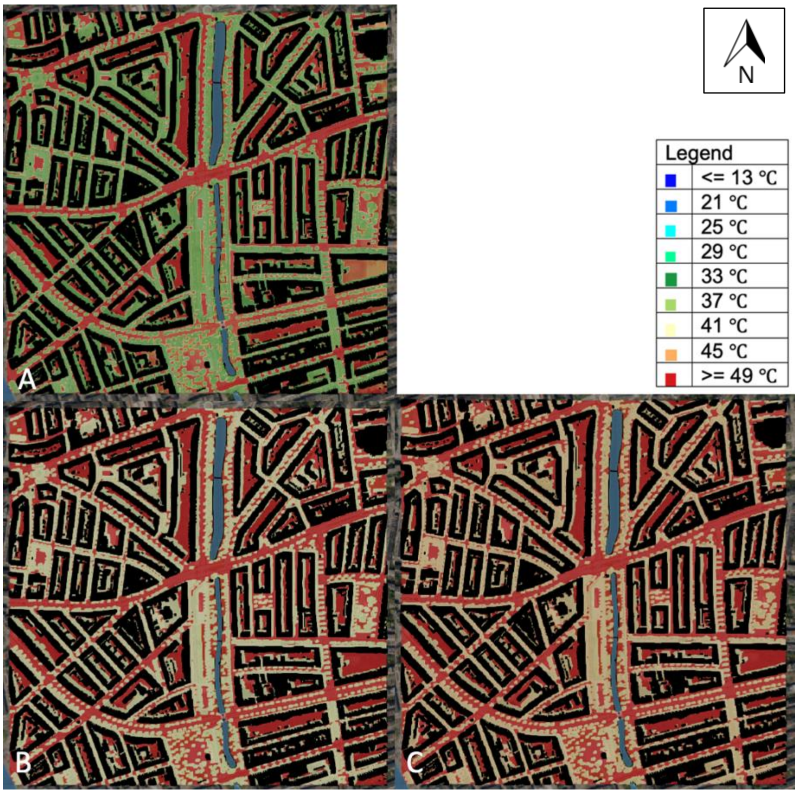

Figure 41: PET in Rotterdam West with original number of trees. The black areas are buildings. Figure A is the PET in the current climate, B in the forecasted climate of 2050 and C in the forecasted climate of 2085. (Scale 1:25,000)

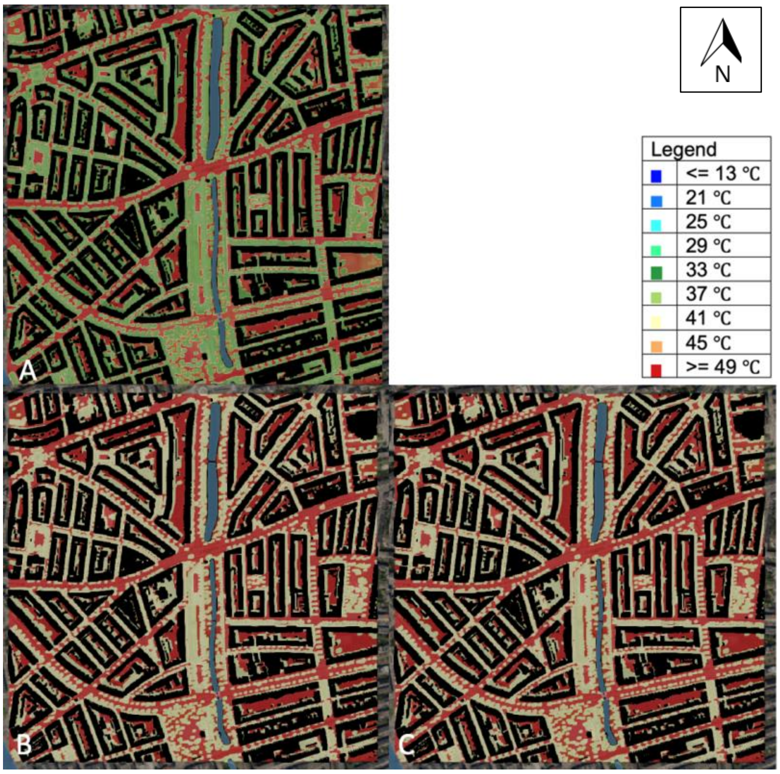

Figure 42: PET in Rotterdam West with an increase of 10% in the number of trees. The black areas are buildings. Figure A is the PET in the current climate, B in the forecasted climate of 2050 and C in the forecasted climate of 2085. (Scale 1:25,000)

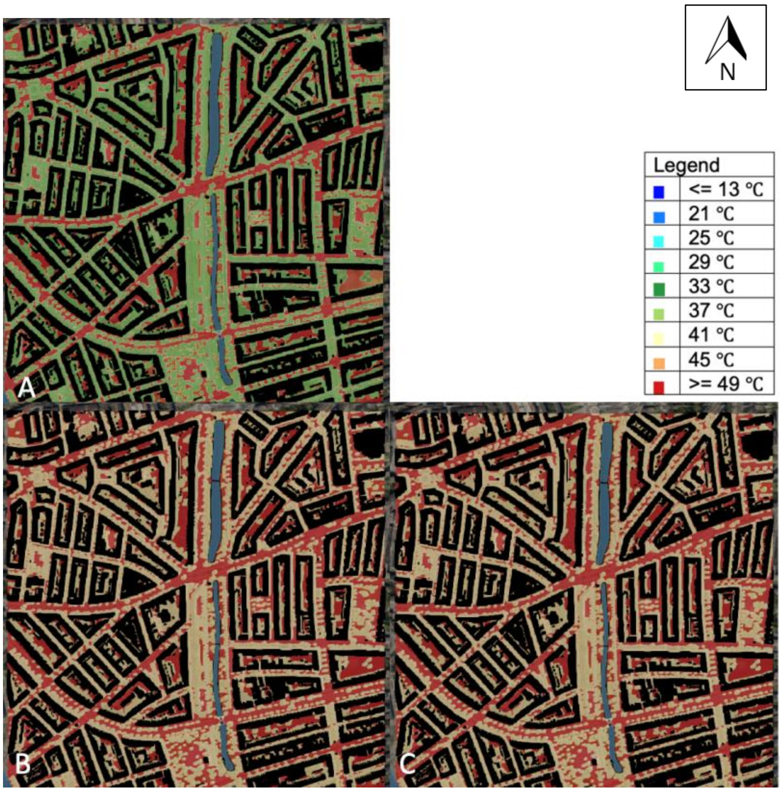

Figure 43: PET in Rotterdam West with an increase of 30% in the number of trees. The black areas are buildings. Figure A is the PET in the current climate, B in the forecasted climate of 2050 and C in the forecasted climate of 2085. (Scale 1:25,000)

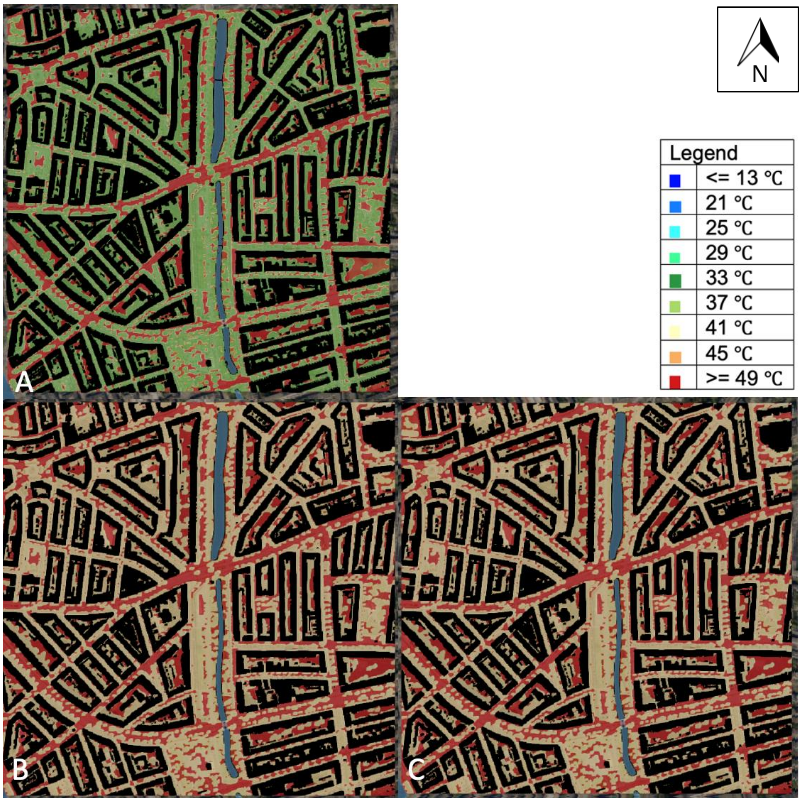

Figure 44: PET in Rotterdam West with an increase of 50% in the number of trees. The black areas are buildings. Figure A is the PET in the current climate, B in the forecasted climate of 2050 and C in the forecasted climate of 2085. (Scale 1:25,000)

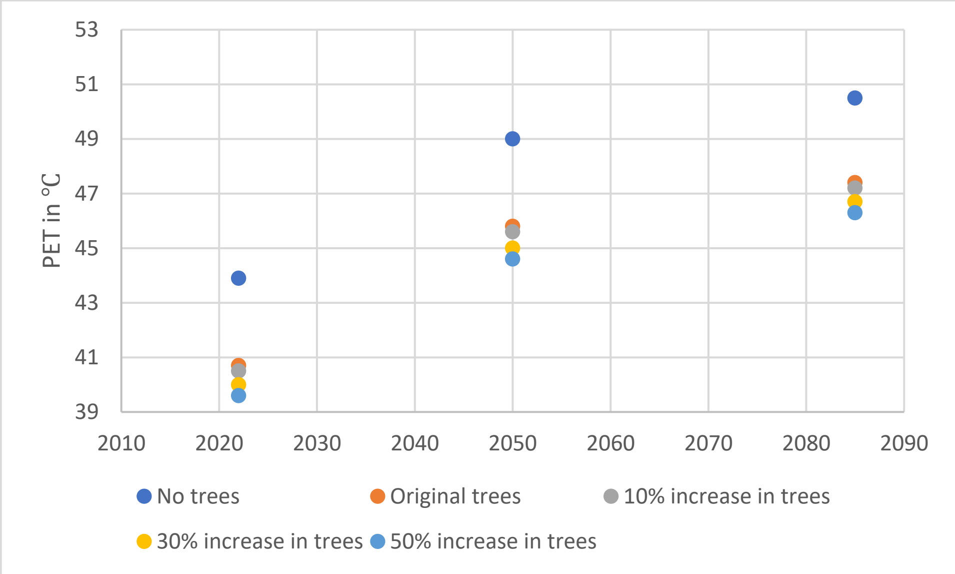

Figure 45: Average PET in the study area for each tree scenario, in the current climate and the forecasted future climates of 2050 and 2085.

The largest part of the surface area has PET values in the class of 35-41 °C and >45°C for all five tree scenarios. Within these two classes, most variation between the different tree scenarios can be seen (Figure 46). Very little of the study area has a PET that falls in one of the other PET classes. The most heat stress is experienced in the highest PET class, which means that the tree-scenario with the smallest part of the surface area in the PET class of >45 °C, and the largest part of the surface area in the lowest relevant PET class, in this case 35-41 °C, experiences the least heat stress. The tree scenario that shows most variation compared to the other tree-scenarios is the model run without any trees.

The difference between the model run without any trees and the other model runs, is even larger in the future climate compared to the current climate (Figure 47). What can be stated from this figure is that the more trees, the less open accessible surface area is in the highest PET class. This means that extremely high PETs can be found in less of the surface area. In the model run without trees, 67.6% of the open accessible surface area has a PET of 45 °C or higher. In the model run with a 50% increase in trees, only 28.0% of the accessible surface area has a PET of 45 °C or higher. This means that in the scenario with a 50% increase, a person is expected to have the smallest change of being exposed to extremely high PET, and thus to extreme heat stress.

In the forecasted climate of 2085, in all of the different tree scenarios, the entire study area falls within the two highest PET classes, 41-45 °C and > 45 °C (Figure 48). This means that in the climate of 2085, extreme heat stress is inevitable, regardless of the number of trees. Still, the models differ in how much of the surface area is 41-45 °C or 45 °C or higher. In the model run without any trees, 69% of the study area has a PET of 45 °C or higher. In the model run with the most trees, where the number of trees has been increased with 50%, the 29% of the study area has a PET of 45 °C or higher.

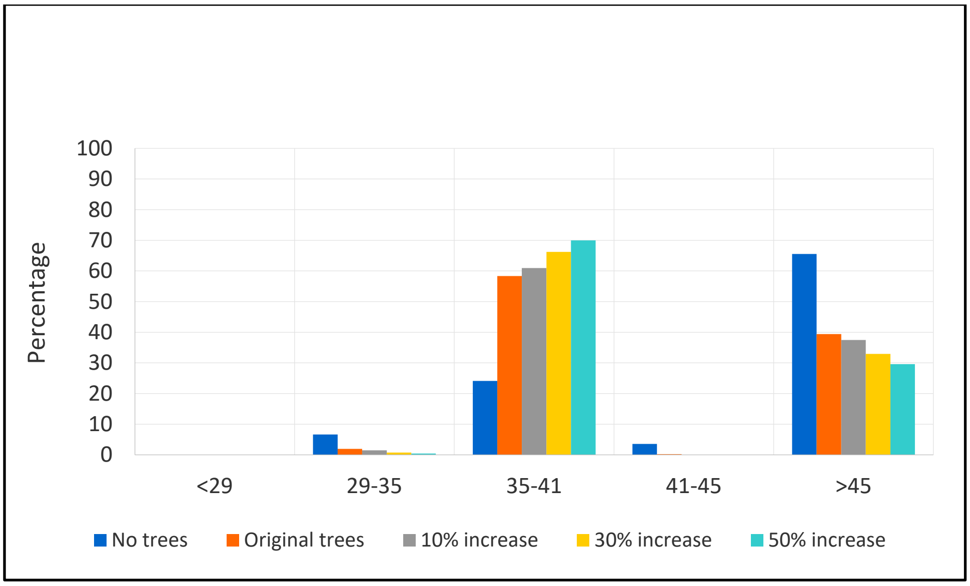

Figure 46: Part of the open accessible area in PET classes on a summer day with a return period of 3 years in the current climate

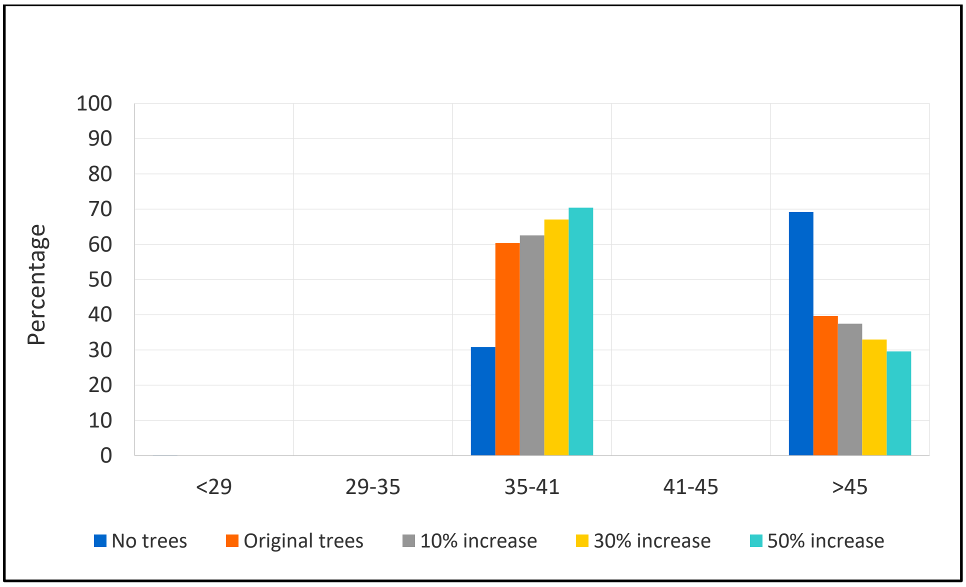

Figure 47: Part of the open accessible surface area in PET classes on a summer day with a return period of 3 years in 2050

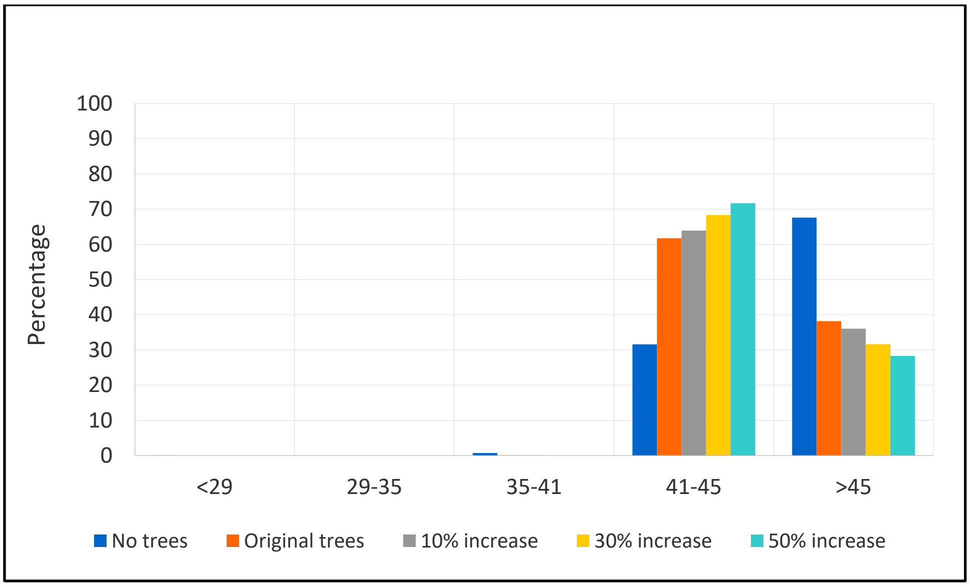

Figure 48: Part of the open accessible area in heat stress classes on a summer day with a return period of 3 years in 2085

4.3.2 The pattern of PET with additional trees

The pattern of PET changes when the number of trees is increased because trees affect shade, wind speed and atmospheric temperature. The difference in PET when the original number of trees is increased as well as the change in the wind speed pattern, is shown here. The pattern of the PET is important because it helps determining the exposure of citizens to heat stress. Therefore, the average PET at distances from buildings is assessed as well.

At many locations where trees have been added (Figure 49), the PET is lower (green areas) than in the situation without the additional trees when the number of trees is increased with 10%. These locations tend to be relatively small and round and seem to be the same size as the foliage of the trees. When the number of trees is increased with 10% in Rotterdam West, the average PET in the current climate is estimated to be 0.5 °C lower. What also strands out is that some parts of the study area are orange or red, which indicates an increase in PET in the situation with additional trees. In most of the study area, the PET does not change due to the increase in the number of trees. Some areas, for example the park in the South of the study area, show varying increase and decrease of the PET.

Large areas of increasing (red and orange) PET can be seen for a situation where the number of public trees is increased with 30% (Figure 50). Many green areas can be seen as well, where the PET decreases as a result of the increase in trees. Similar to the PET when the number of trees is increased with 10%, in the park in the South of the study area locations with increased and decreased PET alternate each other. The largest part of the study area shows no change in PET. The decreasing effect of trees on the PET is very local when the PET is decreasing (green) and seems more spread through the study area when the PET increased (red and orange). Compared to the difference in PET when the number of trees is increased with 10%, the increase of trees with 10 percent has less areas where a decreasing PET can be experienced, however, there an increasing PET can be experienced at more locations as well.

Multiple green spots indicate a decrease in the PET in the study area when the number of trees is increased with 50% (Figure 51). The green locations match the locations of many of the tree stems, indicating that the PET decreases on a local scale because of the presence of a tree. Large red and orange areas indicate an increase in PET in the situation with added trees. The shape of the green and red areas differs, the green areas are smaller, and their appearance is similar to ‘spots’, where the red and orange areas are larger in size and seem to have smoother transitions. The green ‘spots’ can be found somewhat evenly over the entire study area, compared to the red areas which are more abundant in the South-East of the study area. Compared to Figure 29 and 29, the effect of the tree increase of fifty percent has a considerably greater effect than the ten and thirty percent increase. More of the area decreases in PET and at more locations an increasing PET can be experienced.

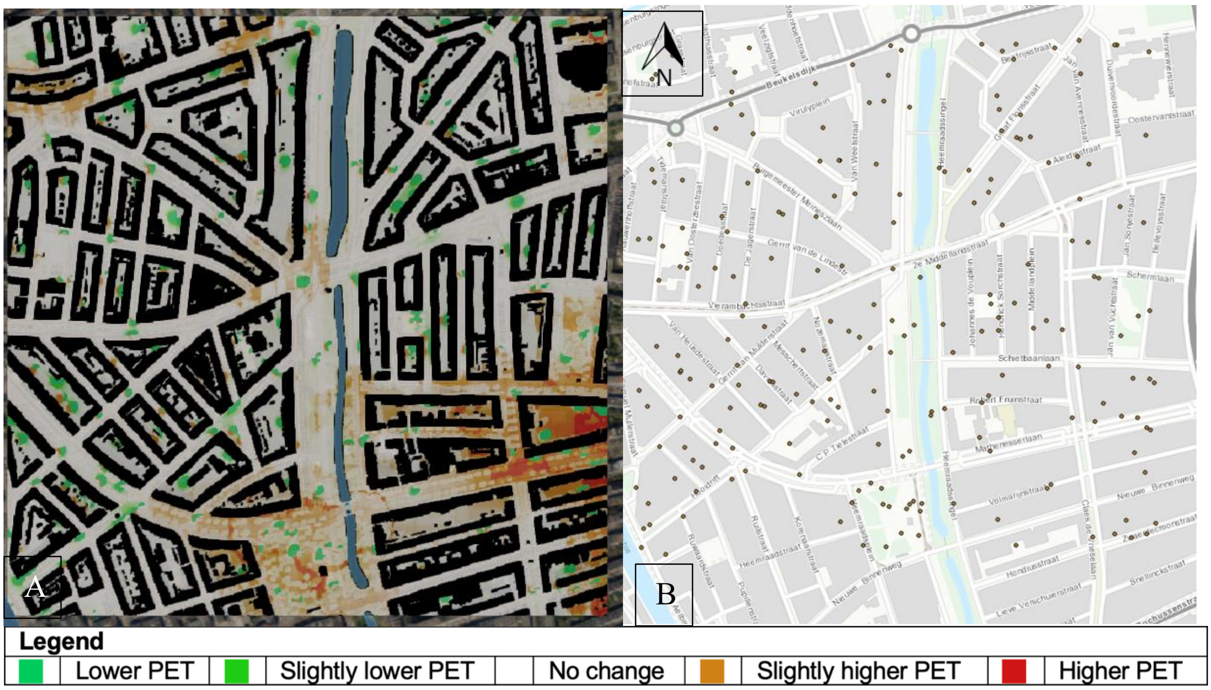

Figure 49: A: the difference in PET with an increase of 10% in tree abundance in the current climate on a hot day with a return period of 3 year. Red areas are increase in PET and green areas show a decrease in PET. B: locations of the stems of the ten percent added trees. (Scale 1:20,000)

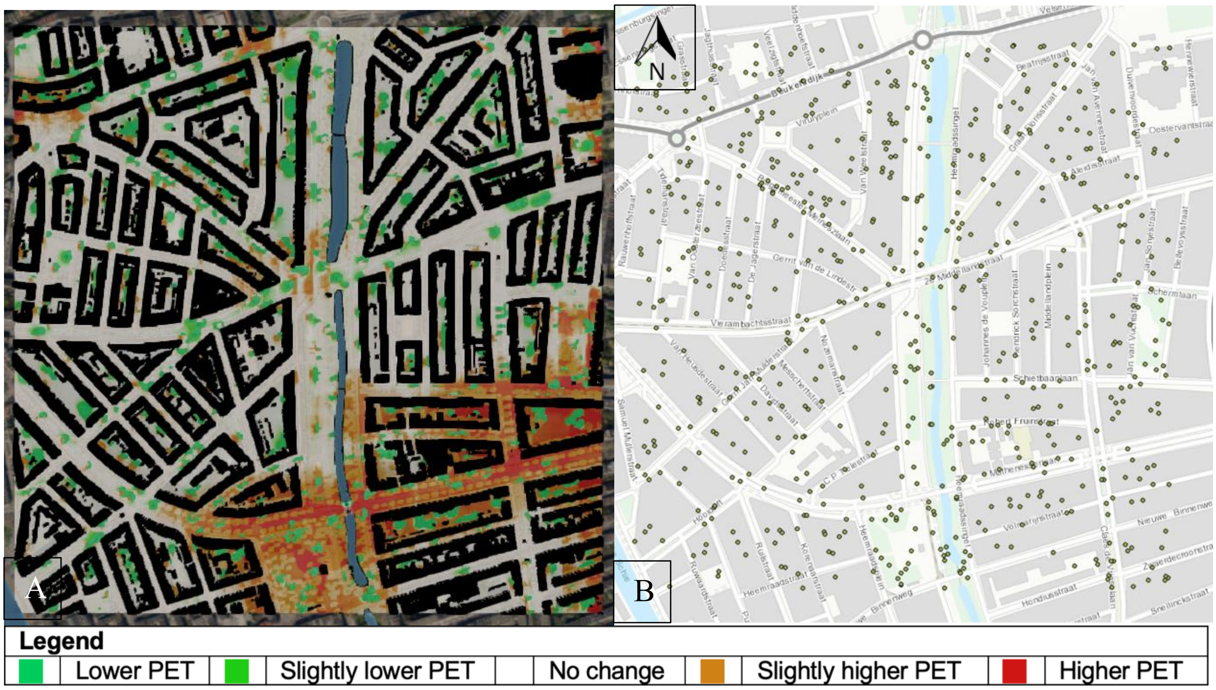

Figure 50: A: The difference in PET with an increase of 30% in the number of trees in the current climate on a hot day with a return period of 3 years. B: the locations of the stems of the added trees with a thirty percent increase. (Scale 1:20,000)

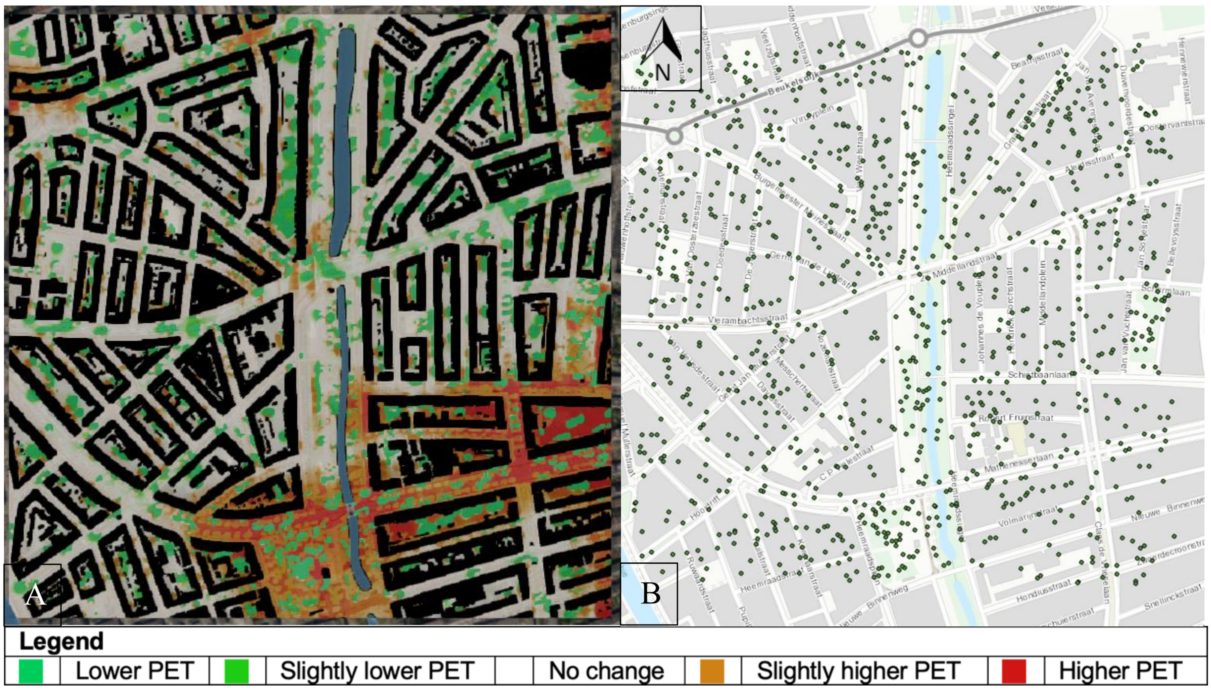

Figure 51: A: the difference in PET with an increase of 50% in the number of trees in the current climate on a hot day with a return period of 3 years. B: the locations of the stems of the added trees with a fifty percent increase in public trees. (Scale 1:25,000)

The wind speed is affected by the increase in the original number of trees in the study area (Figure 52). The locations where the wind decreases are similar for each of the three tree-increases (10%, 30% and 50%). The more trees are added to the model, the more the wind speed decreases. In the park at the south of the study area, wind speed decreases in every scenario. The wind speed decreases in a wide street in the southeast of the study area that leads to the park in every model run as well. The most severe decrease in wind speed appears in the model run that simulated a tree increase of 50% of the original tree count, in the southeast of the study area.

Figure 52: Difference in wind speed for model runs with different increases in number of trees, compared to the original number of trees. Green areas indicate a decrease in wind speed. The brighter the green, the more the wind speed decreases as a result to the increase in trees. (Scale 1:25,000)

4.3.3 Cool places, shade and average PET near buildings

The surface area that is considered cool differs for each of the five model runs (Table 18). The situation that deviates the most from the other model runs is the situation without any trees in the study area. There is variation in the size of the cool areas for the tree scenarios between the current and the future climate, however there is no substantial difference between the two future climate forecasts.

Tree scenario	Current climate	2050	2085
No trees	16.9 %	2.1 %	2.1 %
Original trees	46.3 %	3.8 %	3.8 %
10% increase	49.4 %	4.5 %	4.5 %
30% increase	55.6 %	5.9 %	5.9 %
50% increase	61.0 %	7.3 %	7.3 %

Table 13: Cool areas as a percentage of the total open accessible surface area of each tree scenario and for each climate scenario.

The shade that is calculated in the study area without any trees is the shade that originates from buildings and other structures only. In this situation, the study area does not contain much shade (Figure 53). Without trees, the shade only occurs besides buildings. In parks and open spaces, no shade is present. The most shade is present when blocks of buildings are orientated NW-SE. The most shade in the situation with the current number of trees can be found in parks and along streets, sometimes as long irregular shapes and sometimes as small spots. Most of the area is not shaded with the original number of trees present. When the number of trees in the study area is increased with 10%, the shade is more dominant in parks and along streets, as more random spots of shade can be found. These are most likely the additional trees, as their round shape, small size and random locations indicates. In the scenario where the number of trees is increased with 30%, a large continuous shape of shade can be found in the middle of the study area. In this model output, the shade can be found as random spots, but also along streets and in parks as larger shapes. When the number of trees is increased with 50%, the shape of the locations where shade is present are irregular as well. The shape of the shade mostly consists of dots, spread randomly throughout the study area, and sometimes they form larger shapes.

Figure 53: Shade in Rotterdam West for each of the tree scenarios on June 21st, 2022, 14:00. (Scale 1:20,000)

The percentage of shade on the open surface area as well as the shade on walking routes is highest for the model run with an increase of 50% in trees and lowest for the model run without any trees (Figure 54). All model runs have at least 40% of the walking routes shaded in this part of Rotterdam. In the model run without any trees, the shade is considerably lower, compared to the other model runs.

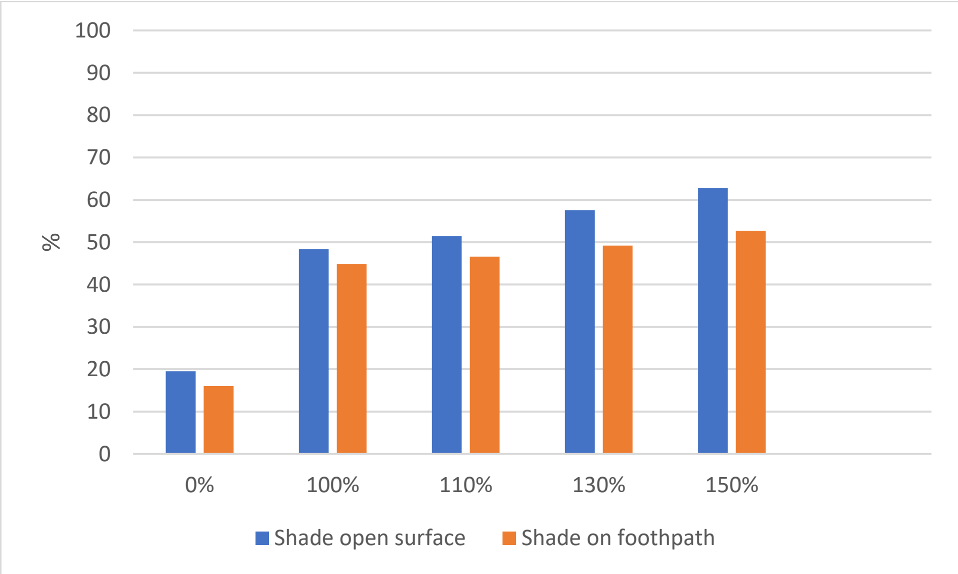

Figure 54: Percentage of the open land surface and percentage of all footpaths (walking routes) that are shaded for each tree scenario in Rotterdam West.

The average PET increases with distance from buildings for each tree scenario in the current climate (Figure 55). The rate of increase in PET is not the same for each of the tree scenarios. For the model run without trees, the PET increases much faster than in the model runs with trees. The largest change in average PET with distance from a building occurs in the model run without trees, the difference in average PET between 3 and 20 meters from a building is 3.2 °C. The smallest change in average PET is measured in the scenario with a 50% increase in trees. The difference in average PET at 3 and 20 meters from a building is 1.2 °C.

The average PET increases in with distance from buildings in the forecasted climate of 2050 (Figure 56). The average PET at 3 meters from a building range from approximately 43 °C in the scenario with a 50% increase in trees to 45.5 °C in the model run without any trees. From 3 to 20 meters from a building, the average PET changes the most in the scenario without trees, with a 3.1 °C difference. In the model run with the least change in PET with distance from a building, the variation between 3 and 20 meters from a building is 1.2 °C.

Similar to the current climate and the forecasted climate of 2050, in each tree-scenario the PET increases with distance from a building in the forecasted climate of 2085 (Figure 57). The average PET is highest in the climate of 2085, compared to the current climate and the predicted climate of 2050. The change is largest in the scenario without any trees, with a difference of 3 °C in average PET at 3 and at 20 meters from a building. The smallest difference in average PET can be observed in the model run with a 50% tree increase, between 3 and 20 meters from a building the PET increases with 1.2 °C.

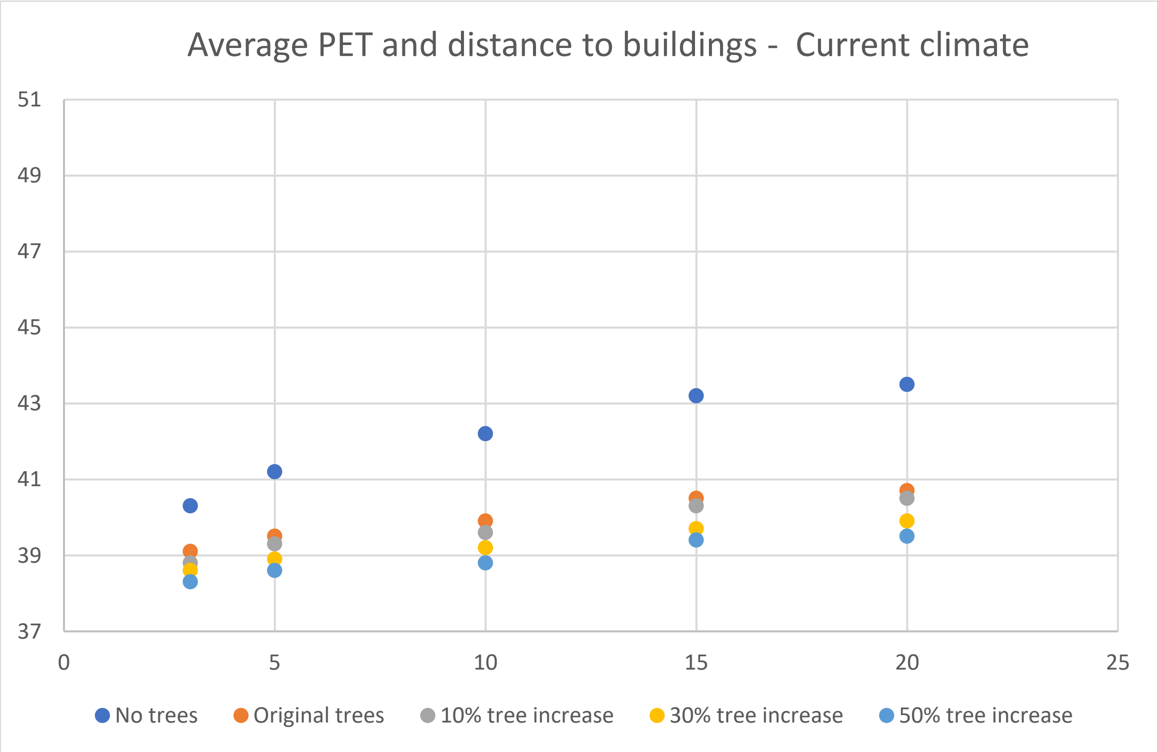

Figure 55: Average PET and distance to buildings in the current climate.

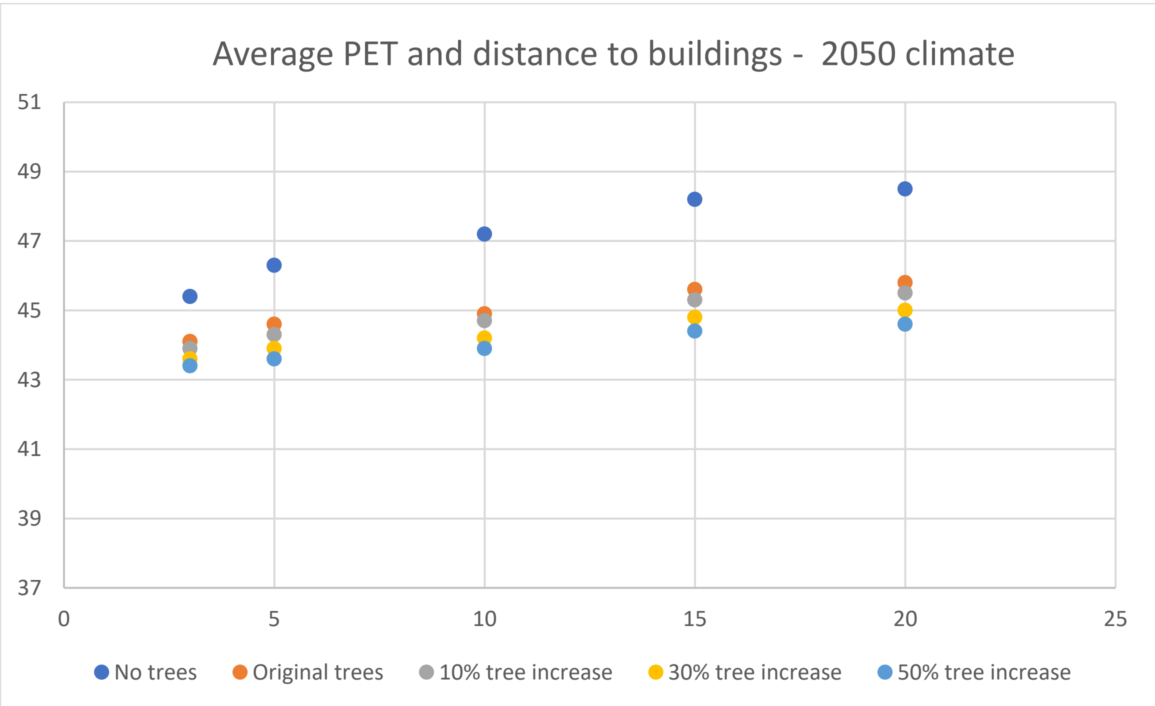

Figure 56: Average PET and distance to buildings in the predicted future climate of 2050.

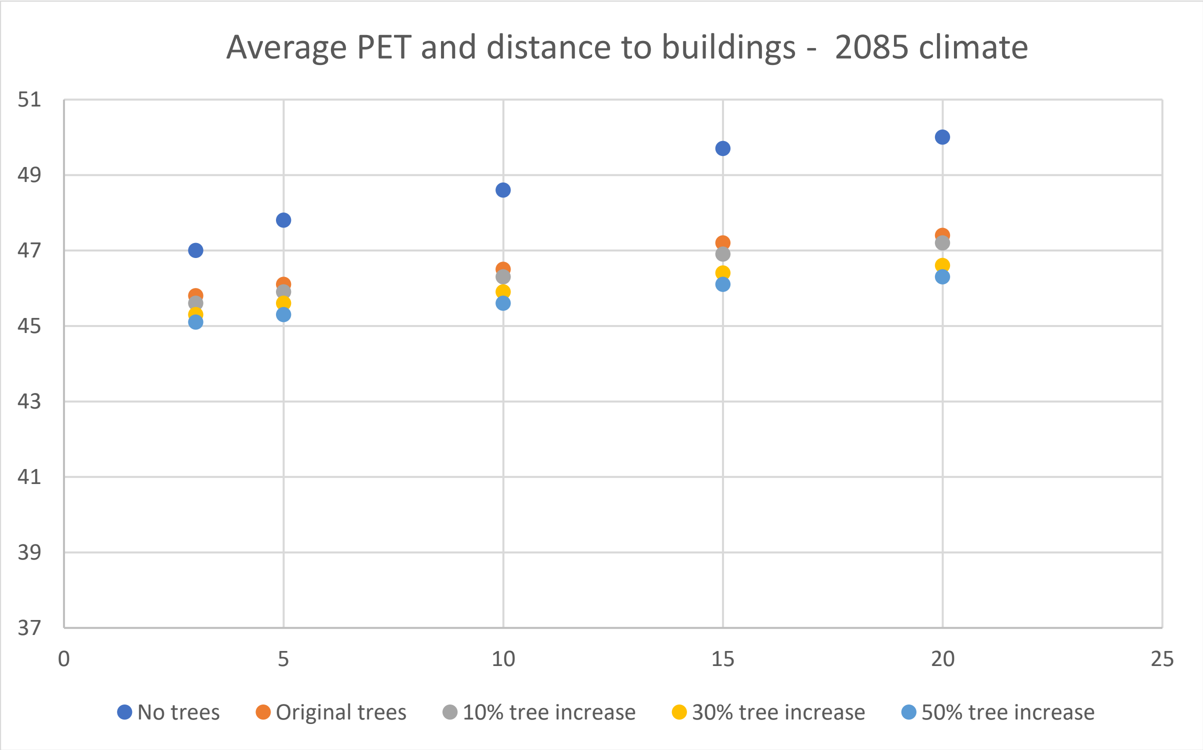

Figure 57: Average PET and distance to buildings in the predicted future climate of 2085.

5 Discussion

5.1 The influence of vegetation on heat stress

Heat stress is related to vegetation, because vegetation driven processes directly and indirectly influence the energy balance of the human body. The presence of vegetation has a considerable impact on heat stress through its effects on shade, evapotranspiration (Dimoudi & Nikolopoulou, 2003). The extent to which vegetation affects the heat stress, greatly depends on the type of vegetation and its arrangement in the environment.

Vegetation provides shade, which helps to reduce the amount of direct sunlight and heat that falls on the surface, people and objects in the environment. The cooling effect of shade is particularly important in areas where temperatures are already high, as it can help to make the environment more comfortable for people and reduce the risk of heat stress. In addition to its direct cooling effect, shading can also have indirect effects on heat stress by reducing the amount of heat absorbed by buildings and paved surfaces. This is because shaded surfaces are cooler than unshaded surfaces, which means that they absorb less heat. By reducing the amount of heat absorbed by surfaces, shading can help to reduce the overall temperature of the urban environment and make it more comfortable for people. This is especially an important effect in urban areas. Trees can provide a considerable amount of shade due to their height and foliage, which can reduce the amount of solar radiation that penetrates through the canopy. In urban areas, earlier research has shown that trees have the potential to reduce heat stress in urban areas by shading open areas (Lindberg et al., 2016). Shrubs and grasses can also provide some shade, but to a lesser extent. This shading effect can have a cooling effect on the human body by reducing the amount of heat that is transferred from the environment to the body through radiation (Equation 1).

Vegetation can also impact heat stress through evapotranspiration, which is the process by which water is released into the atmosphere through transpiration by plants and evaporation from soil and water surfaces. This process has a cooling effect on the surrounding environment by using heat energy from the atmosphere to transform liquid water to water in the gas phase. This process directly lowers the atmospheric temperature, and directly influences the heat stress (Equation 1). This can help to reduce the risk of heat stress by making the environment more comfortable for people. The decrease of atmospheric temperature through vegetation driven evapotranspiration is considered an important benefit of increasing the vegetation in an urban environment (Dimoudi & Nikolopoulou, 2003). Studies have shown that the cooling effect of vegetation through evapotranspiration mostly extends beyond the immediate vicinity of vegetation, and has an overall cooling effect over a city, because it directly affects the UHI (Qiu et al., 2013). In fact, the cooling effect can be particularly pronounced in densely built-up areas where the urban heat island effect is strongest. Trees have a higher evapotranspiration rate than shrubs and grass, which means they can have a greater cooling effect on the environment. However, it should be noted that the effectiveness of this effect may vary depending on the climate and other environmental conditions.

Vegetation can influence the speed and direction of wind flow in the environment. Trees, in particular, can create windbreaks that redirect the wind and reduce its speed. Shrubs and grass can also create some resistance to wind flow, albeit to a lesser extent than trees. When vegetation blocks winds, it decreases the wind speed and decreases the cooling effect of wind. Wind directly cools down the human body, but it also indirectly affects heat stress as it can increase evapotranspiration, by moist air away from vegetation, which increases the potential evapotranspiration. As explained before, evapotranspiration cools down the atmospheric temperature and thus heat stress. Wind is an important factor for determining the heat stress, as it directly affects the energy balance of the human body (Höppe, Peter, 1999). The reduction of wind speed by vegetation has been considered an important disadvantage of increasing the vegetation in the urban environment by previous studies on similar topics, because of its negative effect on heat stress (Ali-Toudert & Mayer, 2007; Koch et al., 2020). All the vegetation driven processes described in this study have a net cooling effect on heat stress, especially in the urban environment (Dimoudi & Nikolopoulou, 2003; Koch et al., 2020; Parsaee et al., 2019; Steeneveld et al., 2011).

As explained in Chapter 2, urban areas tend to be warmer than surrounding rural areas due to the heat absorbed by buildings and paved surfaces. Increasing vegetation cover can help to reduce the urban heat island effect by shading surfaces and providing evaporative cooling of the atmosphere. When surfaces or buildings are shaded, they uptake less heat, meaning that they will radiate less heat during the night. Night-time exposure to heat stress has been proven to be more dangerous for vulnerable groups, as there is no opportunity for the energy balance of the human body to recover from the exposure to severe heat during the day (Oke, 2010).

The effect of vegetation on heat stress occurs not only on a local scale, the processes that are driven by vegetation also interact with climate. Variation in climate is the main driver for the global variation in (Adams, 2009). The occurrence of certain types of vegetation at a location depends on the present climate region. Sudden or gradual changes in climate in an area can come with changes in vegetation over time. There are many studies that focus on the interaction between climate and vegetation on a larger scale (Adams, 2009; Afuye et al., 2021; Theurillat & Guisan, 2001). This study focusses more on the local effect of vegetation on the heat stress on an urban scale, rather than assessing the effect vegetation has on climate regions.

The impact of vegetation is considered in the design and planning of urban and rural environments to help mitigate the impact of heat stress on the population. Planting vegetation that can create shade and transfer heat from the air into evaporation energy as much as possible, without blocking too much wind in an area is considered in urban planning strategies for the mitigation of heat stress. Trees are often considered because they can create much shade with their large canopy covers, have high evapotranspiration rates and can have small, high stems, which reduces the blockages of winds over the ground.

5.2 Heat stress in Rotterdam in the current climate

The selection of the return periods

To assess the heat stress in Rotterdam in the current climate, PET maps were calculated for four different summer days with a maximum daily temperature with different return periods. The four days where chosen based on their probability of occurring, ranging from being reached or exceeded at least once every year, to every 3, 5.5 and 33 years.

The return period of 1 year was chosen because this maximum daily temperature can be expected to occur each year. A summer day with this return period is not necessarily an average summer day, it occurs so frequent that citizens can expect to experience such PET every year. Because of this, the maximum daily temperature with a return period of 1 year is considered a relatively common event. The 3-year return period was chosen because this summer days only occurs or is exceeded every three years and is of greater magnitude in terms of maximum daily atmospheric temperature compared to the summer day that has a return period of one year. The return period of 5.5 years was used because multiple studies use this return period to determine the heat stress in similar areas (Brink, 2020; de Nijs et al., 2019). The probability of a day with such high temperatures occurring is not extremely high, however still high enough that an average person will likely experience such temperatures multiple times during their lifetime. The maximum daily temperature of this day is not as common as the temperature on the days with a return period of 1 and 3 years.

The return period of 33 years is considered a very long period compared to the other three days. The summer days with a return period of 33 years is not necessarily considered to be a good indication of the current climate, because climate is based on temperatures that occur within a period of 30 years, which this return period clearly exceeds. The maximum daily temperature that has a return period of 33 years is considered to be a much rarer, but also a much more severe event than the other 3 return periods. The reference day with a return period of 33 years was included in this study because of its very recent occurrence, to be able to show that even when a certain air temperature has a long return period and a relatively low probability of occurrence, it does not mean that it cannot be expected and heat stress on these types of extreme events is a serious problem. Using this extremely hot day also shows that a climate-resilient city does not necessarily mean that a city is climate-resilient for all weather conditions, because making a region climate-resilient often considers summer days that are expected to occur once every 3 or 5 years. However, this unfortunately does not mean that extreme events such as this do not occur, and that heat stress is a non-occurring phenomenon in 'climate-adaptive' or 'climate-resilient' cities or regions.

Assessing the heat stress in Rotterdam through the four different reference days provides valuable insights into the frequency and severity of more extreme heat events in the urban area. However, it is important to note that these results alone may not be fully representative for the situation of heat stress in Rotterdam in the current climate in more general terms. This is because events of extreme heat can vary in intensity, duration and timing throughout the summer, which all has a considerable impact on heat stress. For instance, a single day with extreme heat stress may not be representative for the overall heat stress experienced throughout the summer. Many studies have proven that most impact on human health and wellbeing is when humans are exposed to extreme heat for longer periods of time (Dong et al., 2020; Kovats & Hajat, 2008). One factor that makes citizens in urban environment especially prone to health risks from heat stress is that in urban areas, temperatures remain rather high during the night because of the UHI (Oke, 2010). This especially causes long-term exposure, as the human body is not able to recover from the exposure to heat stress during the day. This causes the energy balance of the human body to remain in disbalance, causing long term heat stress. By calculating the heat stress for four summer days with different return periods, insights about the probability and severity of heat stress during common or less common events are provided. For city planning strategies, it is essential to assess outdoor heat stress in an urban setting during times of excessive heat stress because it is crucial that certain degrees of heat stress be minimized and residents not be subjected to severe or extreme heat stress on such days (Hoffmann et al., 2018). However, it is also important to consider that factors such as duration, timing, overall summer temperature patterns and the exposure to heat during the night are of great influence on health and comfort of citizens regarding heat, especially for the vulnerable population. This this study, the heat stress during more severe events is assessed, because this gives insight into how often and how severe such events occur, and to what levels of physiological stress the citizens of Rotterdam may be exposed. Insights and knowledge of this can be very important when considering new urban planning strategies. Also, it is often during these common, but extreme, events that the thermal discomfort will be highest at, and that there is a demand for mitigating the heat stress for citizens during such events.

Proportions in PET classes for different return periods

The calculations of the PET for the different reference days give an indication of the grade of physiological stress (Table 1). The most severe case of heat stress in the current climate is the model output with the highest PET values and where in the largest part of the surface area extremely high PET values occur. The most severe heat stress is on the summer day with the maximum daily temperature with a return period of 33 years. The PET is distributed over the study area in such a way that there are no gradual transitions between the highest and lowest PET values, but only abrupt spatial variation in the study area. Over almost half of the open accessible surface area in Rotterdam, extreme heat stress is present. The second to most extreme heat stress can be experienced every 5.5 years. One of the largest differences between the PET that occurs every 5.5 and the PET that is calculated for every 33 years, is that as opposed to the extremer magnitude of heat stress, on the summer day that occurs every 5.5 years, moderate heat stress is present in the study area. Every 5.5 years, extreme heat stress is present in nearly half of the study area. The lowest magnitude of heat stress that is assessed in this study has a return period of one year. Still, for this scenario extreme heat stress occurs in more than a third of the study area. The results of the PET calculations suggest that in areas with fewer structures such as buildings, the level of physiological stress varies less.

The model results suggest that on a summer day with a return period of 1 year, as well as on a summer day that has a return period of 33 years, in the largest part of Rotterdam extreme heat stress can be experienced. Previous research, which used a similar method to determine the average heat stress in Rotterdam for one summer, states that during the summer of 2010, in Rotterdam no extreme heat stress occurred (Nijhuis, 2011). In this study, the spatial differences in heat stress over Rotterdam are evaluated, showing that whilst the average PET over the study area does not indicate extreme heat stress on a summer day with a 1-year return period, the proportions of the study area show that in the largest part of Rotterdam, extreme heat stress actually is present. In the study of Nijhuis, only the average values over the entire city were considered. Therefore, the results of the average heat stress in Rotterdam on a summer day with a return period of one year correspond with the results of Nijhuis. However, the interpretation that no extreme heat stress occurred in Rotterdam differs from the results of this study, as spatial variability in PET values was not assessed in the study by Nijhuis.

What each of the four model runs of the current climate have in common, is that in the entire open surface of the study area, the lowest level of physiological stress that occurs is moderate heat stress. Each of the four model runs have open accessible surface area where extreme heat stress occurs. Even on summer days that occur or are exceeded every year based on their maximum temperature, extreme heat stress occurs in Rotterdam. Heat stress is to be expected in the entire city on a yearly basis and extreme heat stress occurs at least once every year as well at certain locations.

Each of the reference summer days for each return period varied in atmospheric temperature and wind direction. The wind speed, humidity, solar radiation and precipitation were set equal in the model runs. This suggest that differences between the four model runs in this part of the study cannot directly be linked to the differences in atmospheric temperature alone, and that differences in wind direction could cause differences in heat stress as well.

The average PET is higher on the summer day with a return period of 1 year compared to the average PET on a summer day with a return period of 3 years at relatively large distances from buildings. In addition, the area that is considered cool is smaller on the summer day with a return period of 1 year, compared to the area that is considered small on the summer days with return periods of 3 and 5.5 years. This suggests that there is less severe heat stress on the summer day with a return period of 3 years than on a summer day with a return period of 1 year. This outcome is unexpected, because the atmospheric temperature is lower on the summer day with a shorter return period. Because not the atmospheric temperature is lower on the day with the lower return period, and taking PET Equations 6 and 7 from Section 2.3.2 into account, the results of the PET calculation suggest that the difference in wind direction is large enough that it outweighs the difference in atmospheric temperature, and causes a lower PET on the days with a higher air temperature in this case. The results suggest that the PET is very sensitive to wind direction. A cause for this could be that at certain wind directions, the overall wind speed is not as slowed down by buildings and vegetation than other wind direction. This could be because the study area mainly consists of streets that are orientated in similar positions. New questions about the influence of wind speed and direction on the heat stress arise from this unexpected result.

The spatial distribution of PET

The spatial pattern of the heat stress varies throughout the study area for each of the model runs. A few large-scale patterns across the whole city can be seen in each model run. In general, the heat stress is more severe towards the city centre, compared to the surrounding suburbs. Higher levels of heat stress area especially found in smaller streets in densely built-up areas. This suggest that near the city centre, more severe heat stress occurs than outside of the city centre. According to studies that carried out similar results, the UHI is most likely the reason for the increased atmospheric temperature and heat stress in the centre of a city, compared to its less densely built-up surroundings (Steeneveld et al., 2011).

In and near large open spaces, such as broad streets, large squares and the harbour, lower levels of heat stress can be seen. The least heat stress can be seen in parks and along some streets. When looking at the spatial pattern of heat stress within streets, areas near buildings and trees have considerably lower levels of heat stress than other areas. The transitions from lower to higher levels of heat stress are rather abrupt. The pattern of where relatively low heat stress occurs is strongly related to the pattern of where shade occurs in the study area. This is strongly in line with the known cooling effect of shade on heat stress (Armstrong, 1994). For shaded areas, a different equation is used to determine the PET than in non-shaded areas. The abrupt alternation between these two equations when calculating the heat stress in the study area could be a reason for the abrupt differences in heat stress. Thus, the local variation in heat stress in Rotterdam is caused by the alternation of shaded and non-shaded areas. This suggests that in Rotterdam lower levels of heat stress can be found near trees and buildings because of the shade they provide.

The analysis of the difference in the pattern of the PET of the 1- and 33-year return periods suggests that the pattern of the PET is different for different reference days. Each of the reference days is different regarding wind direction and atmospheric temperature. Therefore, the difference in the pattern of the PET can be a result of one or two factors. Various studies have proven that wind is an important factor in the spatial distribution of heat (Abbassi et al., 2022). The reason for the different spatial patterns of the PET is expected to be the result of the difference in wind directions. The difference in atmospheric temperature will most probably cause a difference in the magnitude of the PET values, and the wind direction in the magnitude of the PET values as well as in the pattern of the PET.

There is a difference in the spatial pattern of the PET on the day with a 33-year return period and the day with a 1-year return period. Near transitions between difference-values, small spots with deviating difference-values occur. A cause of this could be that some grid cells are located exactly in a transition zone between two different PET values, due to the grid cell being half in the shade, for example, or half of the grid cell receiving wind with a different speed. When grid cells are located in such zones, the input values are averaged and the output values of the PET calculations are rounded up, which can lead to slightly deviating values, compared to their neighbouring cells.

The spatial distribution of exposure to heat stress

Identifying the exposure of humans to heat stress is very important for the development of strategies to reduce the impact of heat stress on public health and well-being. Assessing the actual exposure of humans to heat stress in the urban environment requires monitoring a range of environmental and individual factors. In this study the decision was made to neglect individual factors and mainly focus on the environmental factors. As for the environmental factors, it is expected that most of the long-term exposure to heat stress occurs indoors, in households or at workplaces, because that is often where people spend most time. The PET calculations in this study are carried out over the outdoor space of Rotterdam, meaning that indoor exposure to heat stress is not assessed. Many studies have been carried out to assess the outdoor exposure to heat stress in various urban areas, as it is very important for city planning strategies (Hoffmann et al., 2018; Lemonsu et al., 2015; Oleson et al., 2015). The exposure of citizens to heat stress is assessed by translating the spatial distribution of the outdoor PET into how humans can potentially be exposed to heat stress.

The average heat stress increases with the distance from a building for each of the four reference days. The model results suggest that the potential of being exposed to more severe heat stress increases with distance from a building because buildings often create shade, and shade creates relatively cooler regions. This implies that locations with higher levels of heat stress can be found further away from buildings. Both trees and buildings create shade, and as trees are often located near buildings on trottoirs and near walking routes, the probability of being in the shade is higher near buildings than far away from them (BGT). For the four model runs in this part of the study, the rate at which the PET increases with distance differs slightly. This is a result of the varying spatial pattern of the PET for the reference days. Because the pattern of the shade is equal for each of the four model runs, the difference in the pattern is thought to be a result of the varying atmospheric temperatures or wind directions in the model runs.

Climate-adaptive cities should meet certain standards, such as maintain a certain walking distance to cool places and a minimum percentage of walking routes should be shaded (Kluck et al., 2020). In this study, cool places are not identified, as information on available seating areas or fountains and swimming opportunities was not available. Therefore, the shaded areas with temperatures below 38 °C, that are eligible to be cool places are presented. To assess accessibility to actual cool places for the citizens of Rotterdam, cool places should be identified in further research and the walking distance to cool places for households should be assessed.

On summer days that have a return period of 5.5 years or lower, nearly half of the study area is considered cool. Because such a large proportion of the study area is considered cool, it can be assumed that cool areas, and thus most probably also cool places, are within walking distance of every household. During summer days with a return period of 33 years, there is very little cool area, suggesting that there are very few cool places where citizens can seek shelter from severe physiological heat stress. Cool areas are determined by the occurrence of PET below 38 °C and shade. Considering that the shade is the same for each of the four PET calculations of the current climate, the extremely small cool area during the day with a return period of 33 compared to the other 3 days depends on the high PET in the study area.

It is expected that during the summer day with the lowest maximum daily temperature, the least heat stress occurs, and the largest proportion of the open surface area is considered cool, compared to the other PET calculations. The cool area on the summer day with a return period of 1 year is smaller than the cool area on the summer days with the return periods of 3 and 5.5 years. Besides atmospheric temperate, the four model runs also differ in wind direction. Earlier research has stated that heat stress in the urban environment is highly depending on wind, as it has a large effect on the distribution of energy (Abbassi et al., 2022). The reason for this unexpected outcome could be that the wind direction influences the distribution of cool air in such a way on the specific day modelled, it causes a smaller part of the shaded area to have a PET lower than 38 °C.

In the current situation of Rotterdam, 45.2% of the open accessible space outside is shaded and 38.8% of the walking routes is shaded. In this study, no distinction between main walking routes and less important walking routes was made. However, the results indicate that the shade in Rotterdam falls just short of the criterium for the minimum percentage of shade on walking routes, that states that important walking routes should be shaded for at least 40% (Kluck et al., 2020). The shade is determined for one specific time of the day only. This means that the shade is not equal for every time of the day, and percentages vary throughout the day. Walking routes that are shaded by a building, can possibly be completely exposed to the sun at another time of the day. Taking this into consideration, the footpaths where shade can be expected for most of the day are the footpaths that have trees nearby.

5.3 Heat stress in Rotterdam in the future climate

Forecasting the PET in the future climate

To assess how heat stress in Rotterdam will develop in the future, the atmospheric temperature was modified in two model runs to simulate the climates of 2050 and 2085. The increase in temperature that was used in the model was based on the W_H-climate change scenario of the KNMI, which is a climate change scenario directly based on the most drastic IPCC climate change scenario (RCP8.5). The probability of the RCP8.5 scenario taking place is uncertain and depends on a variety of factors, including technological, economic, and societal changes that may occur in the future. While some studies have suggested that current trends in energy use and emissions are consistent with the RCP8.5 scenario, others have pointed out that technological innovations, policy changes, and societal attitudes could alter the trajectory of emissions in the coming decades (Intergovernmental Panel on Climate Change, 2018; Rogelj et al., 2016; Van Vuuren et al., 2018). Moreover, the IPCC scenarios are not predictions or forecasts but rather explore possible future pathways based on different assumptions and scenarios. Therefore, the RCP8.5 scenario should not be interpreted as a certain outcome, but rather as a plausible future trajectory that could occur under certain conditions. It is important to note that the probability of the calculated future heat stress occurring depends on the specific climate scenario used in the model run.

Focusing on the W_H-scenario can help policymakers and urban planners understand the potential worst-case impacts of climate change on urban areas. This can help them better prepare for and adapt to those impacts. In addition, using the most severe scenario can help identify the critical thresholds of heat stress that would require urgent action to protect human health and well-being (Huynen & Martens, 2015). The RCP8.5 scenario is a useful reference point for understanding the potential impacts of other climate change scenarios. By focusing on the most severe scenario, a better understanding of how the impacts of heat stress might vary under different scenarios and develop more effective strategies for adapting to those impacts. Overall, whilst there are limitations to modelling the future heat stress for only one scenario, it can provide a useful starting point for understanding the potential impacts of heat stress on urban areas and developing strategies to adapt to those impacts.

Similar to the assessment of current heat stress, future heat stress is assessed by using events of severe heat stress rather than focussing on accumulative heat stress over the summer, exposure to heat stress during the night or heat waves with longer periods of heat stress. One benefit of modelling heat stress for events where more severe heat stress occurs that on a regular summer day is that it can provide a specific, tangible example of what the impacts of heat stress could look like in the future. This can help policymakers, public health officials, and other stakeholders understand the potential risks and take action to mitigate them (Parsaee et al., 2019). Furthermore, by concentrating on a single event, the model can offer more thorough details regarding the elements that contribute to heat stress during a particular event. For instance, with this method the model is able to consider variables that are specific for each day, such as temperature, wind direction or speed, as well as how those variables interact to cause heat stress. This information can be useful for developing strategies to reduce heat stress during that event, such as increasing access to shade or cooling centres, improving building design to reduce heat absorption, or promoting behavioural changes such as staying hydrated and avoiding strenuous outdoor activities (Kluck et al., 2020). The quality of the transformed climate data and the model run assumptions determine how accurately future heat stress will be predicted. As a result, the change in heat stress is as accurate as the downscaled climate change data.

The spatial distribution of PET in the future climate

The proportions of open surface area in certain PET classes varies greatly for the two model runs. In 2050, in approximately two thirds of the open surface area extreme heat stress is determined. In 2085, over approximately the entire open accessible surface in the study area, extreme heat stress is calculated. In neither of the model runs open surface area with a less severe level of physiological stress than ‘strong heat stress’ is found. The increase in heat stress over time is consistent with similar studies on future heat stress in the Netherlands that use the same method for calculating the PET, but use different modelling platforms to carry out their calculations (Koopmans et al., 2018; Molenaar et al., 2016; Steeneveld et al., 2011). The model's findings indicate that the overall severity of heat stress is predicted to worsen over time because of the increased air temperature in Rotterdam brought on by climate change. In addition, as a result of climate change, a larger proportion of Rotterdam's open (public) surface area will likely experience extreme heat stress. The rate of growth of this proportion is so rapid that in 2085, extreme heat stress is expected to be experienced practically everywhere in the research area during summer days that occur at least every 3 years, and possibly even more frequently.

The spatial distribution of regions with lower PET values and regions with higher PET values in the future climates of 2050 and 2085 is comparable to that of the reference day in the present climate. Across the research area, there are trends of rising heat stress from the suburbs to the city centre. Areas close to trees and buildings have relatively low heat stress, whereas places farthest from trees and buildings have substantially higher heat stress. Around buildings and bodies of water, which are also the borders of the region over which the PET is computed, the only change in the geographical distribution of PET values may be detected. This pattern suggests that deviating cell values may occur in the study area due to rounding off values during intermediate calculations.

The difference maps demonstrate that the PET rises uniformly over the whole research area when the ambient temperature is changed. In the research area for each of the several maps, the average PET rises by an amount that is not equal to the amount by which the air temperature rises. For all model runs that are evaluated in this section of the study, the pattern of the PET and the pattern of the difference in PET are the same. The atmospheric temperature is altered, while all other spatial and meteorological conditions are left unchanged in the model runs that evaluate the potential heat stress in Rotterdam. This implies that the geographic pattern of PET in the research is unaffected by variations in air temperature. Nonetheless, increase in atmospheric temperature leads to an increase in PET, which is consistent with the equations for calculating the PET (Equation 6 and Equation 7). The relationship between the increase in maximum daily temperature and the magnitude of the increase in PET depends on the parameters in the two PET equations. This is consistent with the definition of the relationship between atmospheric temperature and heat stress of similar studies (de Nijs et al., 2019).

The spatial distribution of exposure to heat stress in the future climate

In all three climatic scenarios, the average PET rises with the distance from a building, suggesting that the potential to being exposed to high levels of physiological heat stress increases with the distance from a building. The potential heat stress to which citizens may be exposed when leaving a building increases over time, and is most severe in the forecasted climate of 2085. The model results also imply that when the atmospheric temperature rises, the probability to being exposed to more severe forms of heat stress increases when leaving a residence or workplace. It can be stated that the increase in air temperature is of great influence on the range of PET-values that can be anticipated to be found at certain distances from a structure, but little to no impact on the pace at which the average PET from a building grows.

The surface area that has the potential of being considered a “cool place” decreases over time, due to climate change induced rising temperatures. In 2050, the cool area will be nearly ten times smaller than the cool area during a summer day with a similar return period. The cool area in 2085 will be even smaller. The cool areas seem to be restricted to places close to structures or bodies of water where PET calculations are not performed. The cool areas that are present in the future climate, are of such small size that they are unlikely to be labelled a “cool place” (Kluck et al., 2020).

The shade in the open, accessible outdoor space in the study area in the future climate is identical to that of the model runs of the current heat stress in Rotterdam, which is probably due to the spatial input being the same for the current and future model runs. It is questionable if the spatial conditions will actually be comparable in the future. Buildings or other structures that are constructed or demolished in the study area, as well as newly planted or removed trees, can all affect the amount of shade.

The model results demonstrate that under the W_H-climate change scenario, it is probable that by 2050, strong or extreme heat stress would be present in all open, accessible areas of the city on rather common summer days, which can be expected every three years. Extreme heat stress will happen with similar frequency in 2085 throughout practically the whole city. A rise in the atmospheric temperature is predicted by each climate scenario (Attema et al., 2014). The model results show that heat stress will grow as the temperature of the atmosphere rises. It is anticipated that during events of heat stress, that are prone to occur every three years, inhabitants will be exposed to increasingly severe cases of excessive heat stress and that there will be fewer places outside where people may take refuge from it. This implies that Rotterdam does not meet all criteria for being a climate adaptive city by 2050 under the current circumstances.

5.4 The effect of trees on heat stress in Rotterdam

The proportions in PET classes

Over the majority of the study area the calculated PET values fall in the two PET classes of 35–41 °C and >45 °C in the current climate. The fraction of land surface in the extreme heat stress class is greatest in the model run without any trees. When there are trees present, the portion of the surface area that is under strong heat stress grows with the number of trees. As the number of trees increases, the portion of the study area that is under extreme heat stress gradually decreases. This suggests that an increase in trees reduces the amount of extreme heat stress in the study area.

In the forecasted climate of 2050, the entire study area is covered with the two PET classes of 35-41°C and >45°C. In the model runs with trees, the proportion of the study area in extreme heat stress decreases with the increase in number of trees. Likewise, the proportion of the study area where strong heat stress can be experienced increases with the number of trees. In comparison to other model runs, the fraction of the study area that potentially experience extreme heat stress is considerably higher in the model run without any trees. These results also imply that the proportion of the study area under more severe heat stress decreases when the number of trees increases.

In 2085, in the majority of the study area the PET values are within the 41-45 °C and >45 °C classes. This shows that no lower degree of physiological stress than extreme heat stress is anticipated to occur in approximately the entire study area. The proportions of the study area that are in the highest PET-class decrease with increasing number of trees. The proportions of the study area in the lower PET-class are essentially the same in this regard. This suggests that increasing the number of trees in the study area makes the heat stress less severe.

The average PET in the study area decreases with the number of trees for each climatic scenario. The highest average PET can be found in the forecasted climate of 2085, for each tree scenario. These results also imply that the heat stress decreases with an increasing number of trees. The implications on the decrease in heat stress due to an increase in vegetation cover are consistent with results in other studies that assessed future heat stress in a large agglomeration in the Netherlands (Koopmans et al., 2018). Koopmans et al. stated that the increase in trees can have considerable effect on decreasing future heat stress, however climate change will have a larger impact on future heat stress than the imposed mitigation measures.

The effect of trees on the spatial distribution of PET

The spatial distribution of the PET differs for each tree scenario. The results of the five different tree scenarios show more variation in the spatial distribution of the PET in the current climate compared to the future climate scenarios. This is probably a result of the parameters in the PET equations, as the parameters are calibrated on the current climate in Wageningen, the Netherlands, where extremely high temperatures, as the temperatures in the future climates, are not expected (de Nijs et al., 2019). When the atmospheric temperature is of such a magnitude as in the future climate predictions, the effect of atmospheric temperature weighs extremely heavy compared to the other factors in the PET equation, making other factors of less influence and thus a decline in the spatial variation appears.

When looking at the changes in PET over the study area, the locations of the newly inserted tree-stems and the areas of decreasing PET-values appear to be related. Compared to the PET maps of the study area with fewer or no trees, the PET maps of Rotterdam West with more trees reveal much more relatively cool places. The cooler places may be caused by the shadow provided by the trees, as indicated by the shade maps and the spot-like appearance of the locations with lower PET values. This implies that an increase in tree cover reduces heat stress locally. When the number of trees increases, fields with increased heat stress also arise in the study area. It does not appear that the specific placements of the stems of the additional trees are related to the areas where the temperature rises. Strong correlations exist between the patterns of decreasing wind speed and the places with rising heat stress. These findings reveal that an increase in trees may result in areas of decreased wind speed that result in an increase in the PET, indicating that trees may potentially also have an unfavourable impact on heat stress. This is strongly in line with earlier research that assesses the impact of wind on heat stress in the urban environment (Hunt & Watkiss, 2011; McCarthy et al., 2010).

Particularly in the southeast of the research region, the wind speed reduces more than it does elsewhere. Wide, east-west oriented streets and parks appear to be places where the wind speed reduction is greatest. The wind direction used in the model is 93 degrees, which indicates that the wind comes from the east. This suggests that wind speed reduces most in open areas such as parks and squares, east-west streets, and sites where wind speed is predicted to be high. It is implied that wind speed is more influenced where it is believed to be greatest by the fact that it lowers most at these sites. The model results do not show what effect the placement of trees has on the wind speed pattern, however, according to earlier research, the location of trees certainly has an effect on wind speed patterns and thus heat stress (Abbassi et al., 2022; de Nijs et al., 2019; Hanipah et al., 2016). The wind speed at a certain location is affected by the spatial circumstances and highly dependent on the direction from which the wind originates.

The cooling effect of the increased vegetation cover through evapotranspiration cannot be distinguished from the model results. The effect of evapotranspiration is considered in the PET calculations, by decreasing the effect of the UHI, due to the increase of the vegetation fraction. Because the UHI occurs on a large scale, over the entire city, local variation in evapotranspiration is not considered when calculating the PET. Although the cooling effect of increased vegetation cover through evapotranspiration on heat stress cannot be distinguished from the model results clearly, research has shown that vegetation cover can provide considerable relief to urban residents experiencing heat stress (Ali-Toudert & Mayer, 2007; Dimoudi & Nikolopoulou, 2003; Susca et al., 2011). Furthermore, studies have shown that increasing the amount of vegetation cover and green spaces in urban areas can provide multiple benefits, such as improving air quality, reducing noise pollution, and enhancing the overall well-being of urban residents (Chen, D. et al., 2014; Qiu et al., 2013; Shiflett et al., 2017).

The scenario without any trees has the least amount of shade, and consequently also the least wind blockages caused by trees. The heat stress is most severe for the scenario without any trees, in each climatic scenario. This implies that the shade offered by trees is of larger effect than the windbreaks trees cause on the overall heat stress in the study area. This suggests that the ability of trees to provide shade has a greater impact on the study area's overall heat stress than their ability to provide windbreaks.

The effect of trees on the spatial distribution of exposure to heat stress

The average PET increases with distance from a building for each tree-scenario, in the current climate as well as in the two forecasted climates. In the current climate, strong heat stress is experienced in each tree scenario, for distanced from 0 to 20 meters from a building. In the scenario without any trees, extreme heat stress is experienced directly outside of buildings, and increases with distance from buildings. For citizens of Rotterdam, the probability of being exposed to more severe levels of heat stress when leaving a residence or workplace decreases with the number of trees in the study area. The probability of being exposed to more severe levels of heat stress increases with distance from a building.

In the forecasted climate of 2050, regardless of the number of trees, citizens of Rotterdam are expected to be exposed to extreme heat stress when leaving a building. This is the same for the forecasted climate of 2085, where PET values are even higher compared to the climate of 2050. Even though there is not a more severe level of physiological stress defined in this study, it is assumed that heat stress still increases with increasing PET, even when already classified as extreme heat stress, according to findings of similar studies (Koomen & Diogo, 2017).

The model's findings demonstrate that as the number of trees grows, so does the surface area that is considered cool and has the potential to be called a "cool place". The proportion of the surface area that is classified cool in the current climate compared to the forecasted climates differs considerably. The proportion of the surface area that is considered cool in 2050 is the same as in 2085. In the current climate and with the original number of trees, it is expected that all citizens have access to cool areas within walking distance. These findings suggest that as the number of trees grows, so do the size or quantity of areas where residents can seek refuge from exposure to severe heat stress.

The cool areas in the future climates are approximately 10 times smaller than the cool areas in the current climate. In the future climate, the largest cool area, in the model run with the most trees, is still considerably smaller than the cool areas in the current climate. This suggests that in the future climate, despite an increase in tree cover, not all residents will have access to cool places, and as a result, not all residents would be able to find relief from severe heat stress in the open urban environment. Planting more trees will not be adequate as a single and only measure to reduce inhabitants' exposure to heat stress, according to the low percentages of surface area that are considered cool in the future climates of 2050 and 2085. To mitigate the increase in heat stress caused by climate change, more actions need to be performed. The findings show that, while a mitigation strategy to combat heat stress that increases the number of trees will help to reduce heat stress, it will not be sufficient on its own.

With the current number of trees, in Rotterdam West the criterium for the minimum percentage of shade on walking routes is met, according to the guidelines for climate adaptive cities (Kluck et al., 2020). This is contradictory to the results of the shade on walking routes over the whole city. This suggests that the shading on walking routes differs per neighbourhood.

5.5 The effect of trees on future and current heat stress

Heat stress is affected by vegetation in more ways than one. As the results present, vegetation has a decreasing effect on heat stress, because of the shade it provides. Also, vegetation has a decreasing effect on heat stress because it influences the latent and evaporation heat ratio in the atmosphere (Dimoudi & Nikolopoulou, 2003). Wind can reduce heat stress by directly affecting the energy balance of the human body, but also by affecting evaporation, which is why wind can reduce heat stress. Vegetation, such as trees, can block wind and thereby decrease the wind speed. Therefore, increasing the vegetation cover can reduce heat stress, but it also has the ability to slightly increase heat stress.

The impact of trees on heat stress is similar in both the present and the predicted future climates of 2050 and 2085. Trees have the ability to create shaded areas, which can mitigate heat stress in comparison to non-shaded areas. With rising temperatures expected in the future as a result of climate change, shaded areas are anticipated to become even more critical, as extreme heat stress is likely to become more frequent and severe. Although increasing the number of trees can lead to a slight rise in heat stress in specific locations due to their impact on wind, the mitigating effect of trees on heat stress is more important than their increasing effect. The shade trees provide does not only have a cooling effect during the day, but it also prevents buildings and surfaces from taking up heat from the sun during the day, which prevents them from radiating heat at night. Exposure to heat during the night can cause serious health consequences because the body is unable to recover from the heat stress experienced during the day (Oke, 2010). This occurs due to an imbalance in the body's energy balance caused by exposure to heat during the day, which is prevented from being restored at night due to continued exposure to heat. Increasing the number of trees in Rotterdam can help to decrease heat stress to some extent. However, the findings suggest that merely increasing vegetation in urban areas is insufficient to counteract the impact of rising temperatures caused by climate change. To minimize heat stress in the urban environment, a combination of measures must be implemented.

5.6 Reflection on research strategy and recommendations for future research

The PET is a measure of how a person perceives air temperature and atmospheric conditions. It takes into account meteorological and spatial factors, which can be quantified, but the way individuals experience these factors can vary based on various factors such as activity, clothing, gender, and health. The severity of physiological heat stress is determined using a standard heat stress test established by the RIVM. This approach to PET is commonly used in similar studies, and deviating from these definitions can lead to confusion and misinterpretation of results (de Nijs et al., 2019; Koopmans et al., 2018; Steeneveld et al., 2011). Previous research has shown that people from different climate regions experience thermal circumstances differently and that the effect of heat on humans decreases over time, for example, a person is more used being exposed to certain temperatures by the end of the summer than at the beginning (Folkerts et al., 2020; Harlan et al., 2006). To obtain a comprehensive understanding of how vegetation affects heat stress in urban areas in the Netherlands, the definition of physiological stress for the Dutch population should be assessed in relation to the impact of vegetation.

The effect of evapotranspiration on heat stress in Rotterdam was not directly assessed in the outcomes of the model results in this study. The effect of evapotranspiration on the heat stress in the model used in this study is considered by the effect of the vegetation fraction in the area on the UHI. The first reason for this is that the cooling effect of vegetation could be correlated directly to the pattern of the shade. In addition, the cooling effect of vegetation through evapotranspiration is thought to be visible on larger scales, as the increase in evapotranspiration affects the UHI. Because the cooling effect of vegetation through evapotranspiration was not assessed on a local scale as well, it is possible that the cooling effect of increasing the vegetation cover on heat stress is underestimated in this study. Further research should focus more on the cooling effect of evapotranspiration on the environment in Rotterdam. To assess the effect of evapotranspiration only, a model that also includes the local effect of evapotranspiration on the heat stress should be used to carry out PET calculations during the night, to eliminate the cooling effect of vegetation through shade.

The assessment of future heat stress done here relies on a single climate change scenario, but the actual heat stress may deviate from this. As estimating future heat stress is challenging due to the many uncertainties associated with it, it is advisable to consider a range of potential outcomes in the assessment of future heat stress. To do this, multiple climate change scenarios should be taken into account, as it is likely that the actual climate will be somewhere in between these scenarios. The KNMI confirms that the actual climate change will most likely fall somewhere in the middle of the four climate change scenarios (KNMI, 2014). While this study only considers temperature rise for future climate data due to time constraints, it is essential to consider other meteorological factors prone to change under climate change when assessing urban heat stress in Rotterdam in further research. By estimating heat stress for various climate change scenarios, the range in which heat stress can occur can be determined, providing a better understanding of the potential outcomes. This approach will help to address the uncertainty associated with future heat stress estimation.

Climate change can have an impact on a number of tree characteristics, including canopy density and growth rate (Richardson et al., 2013). Vegetation is restricted to climate regions. Climate regions have a tendency to move as a result of climatic change, which means that in the future, some tree species will no longer thrive in Rotterdam's local environment (Adams, 2009). Further research is needed to determine which tree species have the characteristics necessary to produce shade, disrupt wind speed the least, and thrive with the least amount of "assistance" in the predicted climatic zone that Rotterdam will be in.

Determining the exact wind speed from interpolated wind measurements at a specific location in the study area is very complex. The direction of the wind, as well as the wind speed is measured at a weather station and is transformed to the urban environment by means of multiple interpolation and integration methods. The wind speed is of great influence of the PET, as wind speed directly affects the convective heat flow (Equation 1). This, together with the results suggests that the accuracy of the calculated PET at a certain location is very sensitive to the accuracy of the wind calculations. Air circulation and wind patterns tend to change tremendously with the climate, especially in the W_H-climate change scenario (Attema et al., 2014). This makes it very difficult to forecast urban wind patterns in the future climate. To gain a comprehensive understanding of the exact effect of trees on wind and thus heat stress, further research is required.

It is essential to note that the study evaluates heat stress during the hottest hour of very hot summer days, and the negative effects of heat stress often persist into the night due to the urban heat island effect (Kovats & Hajat, 2008; Lemonsu et al., 2015; Oleson et al., 2015). In addition, the model only evaluates outdoor spaces, as the equations used for assessment are not based on indoor conditions. Because most people spend the majority of their day indoors, it is crucial to evaluate indoor exposure to heat stress in urban areas and how climate change will affect it. It will be interesting for future research to document the effect of long-term as well as night-time exposure to high PET values on human health and comfort.

To assess whether Rotterdam qualifies as a climate adaptive city, further research should determine the distance between residences and actual "cool places" that meet all the required standards, to assess the exposure of the population to heat stress (Kluck et al., 2020). Also, further research should assess the activity of the population and look at locations that are usually more crowded and times of day at which people are most outside and active to assess the actual expose to heat stress even better.

The advice for the municipality of Rotterdam is to carefully analyse the results of this study before drawing any conclusions about the effect of trees on heat stress. The results are complicated and dependent on multiple spatial and meteorological factors. Instead of solely assessing the effect of trees on heat stress during the hottest hour of the hottest summer days, the municipality of Rotterdam needs to also evaluate the effect of trees on long-term exposure to hear stress and exposure to heat stress during the night. The current model does not indicate any reduction in physiological stress due to trees. However, the study does not reveal the direct health effects of citizens because the negative health effects of exposure to heat stress occur mostly indoors and during longer period of times. Therefore, it is crucial to evaluate the effect of trees on long-term heat stress and indoor heat stress before making any mitigation strategy decisions.

6 Conclusion

Vegetation has an important impact on reducing heat stress through its ability to influence shade and evapotranspiration rates. However, the influence of vegetation on wind can slightly increase heat stress. The type and arrangement of vegetation in an area have varying effects on reducing heat stress. In urban planning strategies, increasing the vegetation cover is considered beneficial for the mitigation of heat stress.

In the current climate, the lowest degree of physiological stress that occurs in the open surface of the study area on a yearly basis is moderate heat stress. Extreme heat stress is present in Rotterdam, even on summer days that occur or are exceeded every year, based on their maximum daily temperature. With decreasing frequency of occurrence of the summer days based on their maximum daily temperature, the overall severity of heat stress increases, as well as the proportion of the surface area where extreme heat stress can be experienced. Thus, events where extreme heat stress may be experienced occur at least once every year, and on less frequent hot days the severity of heat stress increases and the proportion of the surface area where extreme heat stress can be experienced increases.

It is expected that heat stress in Rotterdam will increase tremendously over time for the W_H-climate change scenario. It is expected that by 2050, during relatively frequent summer days, which may be expected every three years, strong or high extreme heat would be present in all open, accessible surface area of the city. It is forecasted that in 2085, the occurrence of extreme heat stress will be experienced over the majority of Rotterdam during events that will take place every three years. When the atmosphere's temperature increases, heat stress will worsen. The magnitude of the increase in heat stress depends on both the rise in ambient temperature and the effect of the temperature rise on the other elements impacting the PET.

Increasing the number of trees in Rotterdam can reduce heat stress to some extent, but even an increase of 50 percent in the number of trees will not be enough to reduce the level of physiological stress in the current, as well as the future climate. Trees can decrease heat stress in Rotterdam by providing shade and influencing the evaporation heat ratio in the atmosphere, but the effect is not strong enough to counteract the increasing atmospheric temperatures caused by climate change. The ability of trees to provide shade has a greater impact on heat stress than their ability to cause windbreaks. Relatively cooler regions can be found in the shade of buildings, but wind may also be important for creating areas with less heat stress.

The study points out that there is currently strong to extreme heat stress on summer days with a high probability of occurrence in Rotterdam. Additionally, the heat stress is expected to worsen and become pervasive in the future. Planting trees in suitable locations can help alleviate heat stress in the city, but it may not be sufficient to combat the heat stress caused by rising temperatures. Reducing inevitable future heat stress caused by climate change requires more mitigation strategies than one, and it is expected that increasing the vegetation cover can certainly help in the mitigation of heat stress. The assessment of heat stress during various events of more, or less, extreme heat has proven to provide valuable insights that are important for city planning strategies in reducing the outside exposure to extremely high levels of heat stress. It is important to note that long-term and night-time exposure to heat stress have the most risk on the public health and should be considered too in urban planning strategies.

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Appendix A

Return period maximum temperature	(%) PET 29 – 35 °C	(%) PET 35 – 41 °C	(%) PET 41 – 45 °C	(%) PET >45 °C
33 years	0	19	2	43
5.5 years	1	20	10	33
3 years	14	9	24	17
1 year	20	8	22	14

Table A1: Percentages of the research area below, between and above certain physiological equivalent temperatures in the current climate

Model run (RP or year)	**Cool areas (m^2)**	**Part of open space**
RP 33 years (current climate)	2.35 x 10^6	4.9%
RP 5.5 years (current climate)	2.09 x 10^6	44.6%
RP 3 years (current climate)	2.09 x 10^6	44.6%
RP 1 year (current climate)	2.07 x 10^6	43.9%
RP 3 years (2050)	2.41 x 10^5	5.1%
RP 3 years (2085)	2.35 x 10^5	4.9%

Table A2: Overview of the size of the cool areas in the current and forecasted future climate.

Figure A1: Model run 1.2.2: Wind direction 2018 (292 degrees), RP 5.5 years (Scale 1:200,000)

Figure A2: Model run 1.2.3: Wind direction C (112 degrees), RP 5.5 years (Scale 1:200,000)

Figure A3: Model run 1.2.4: Wind direction 2018 D (22 degrees), RP 5.5 year (Scale 1:200,000)

Appendix B: Digital Appendix

The digital appendix contains the most important model results. The digital appendix includes the PET calculations of the five different tree scenarios, for the three climatic scenarios.