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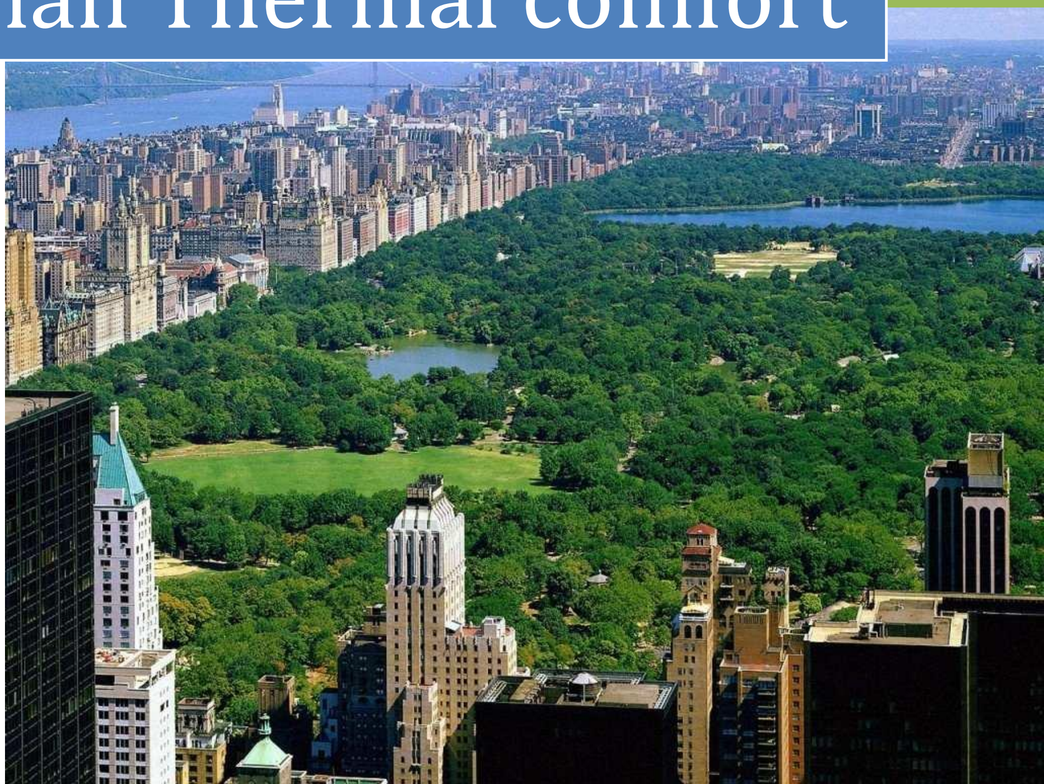
Mesoscale modelling the influence of urban vegetation on the Urban Temperatures and Human Thermal comfort



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Mesoscale modelling the influence of urban vegetation on the Urban Temperatures and Human Thermal Comfort

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Msc. Thesis Meteorology and Air Quality

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Preface

With a background as spatial planner, I experienced the attempt of urban meteorology to take a guiding role in urban planning. The meteorologists set standards with generic and hard norms by so called ‘climatope maps' (Scherer et al., 1999) or homogeneous climate-response units (Alcoforado et al., 2009). In my Bachelor thesis I implemented these norms in a specific case: A new design of the Avenida da Liberdade in Lisbon. It was hard to get an optimal balance between generic meteorological knowledge and the specific approach of urban planners. Especially the effect of vegetation on the mesoscale level of the city was unclear.

By writing this master thesis I am aiming to give the spatial planning a more guiding role. By taking into account the current developments of green in urban planning, I want to discover the most optimal way between both disciplines to mitigate the Urban Heat Island effect on the mesoscale level. Therefore, the development of creating handles with regards to urban vegetation for spatial planners is the main goal of writing this research.

Abstract

Urban Climate is becoming a more important issue in urban planning processes and the way cities are organized. Especially, in combination with increasing global urbanization and climate warming it is of great importance to keep cities liveable. Urban morphology, pollutants and changes in albedo, anthropogenic heat and vegetation are effecting the radiation balance compared to the rural area. Temperature differences between the city and its surroundings are the consequence. This so called Urban Heat Island (UHI) effect might be mitigated by adding more water vapour in the air. More vegetation leads to more evaporation which might lead to lower air temperatures in the urban area and therefore a mitigation of the Urban Heat Island effect. By using the WRF mesoscale model this hypothesis is investigated. An academic city is designed to generate general advice for mid latitude cities. The outcome of this research is that the cooling effect of urban green is dependent on the availability of soil moisture, the vegetation type, the way vegetation is distributed with respect to the wind direction and sizes of urban parks. A higher soil moisture content increases the evaporation and therefore causing a decreasing temperature. At the same time human comfort decreases due to a higher humidity level. Bigger parks mitigate the UHI downwind of the park more, while more equally spread vegetation has a bigger cooling effect on the entire city. The evaporation of vegetation and soil moisture increases the humidity of the air, which mitigate the cooling effect in terms of human comfort. The final results may give urban planners insight into the effect of urban green on urban meteorology and human comfort. This knowledge could add weight to urban climate in all the weighs urban planners have to make in their decisions.

Key words: Mesoscale modelling, Urban heat island, Urban vegetation, Human comfort

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1. Introduction

Currently, about half (52.1%) of the people on earth is living in urban areas in 2011 (United Nations, 2011). The next decades this amount is projected to increase up to 67.2% in 2050. Moreover, 49.1% of the city dwellers lives in towns with more than a half million inhabitants. Also projected climate change will probably leave her mark on the urban area. In a future warmer climate with increased mean temperatures, climate modeling results indicate that heat waves would become more intense, longer lasting, and/or more frequent (Meehl and Tebaldi, 2004). The joint trends of urbanization and climate change are the main components of research in urban climatology. A combination of a warmer climate and urbanization will cause a bigger interest of city planners in urban meteorology to optimize their plans (Mills, 2006). A consequence of neglecting these current developments in urban planning, could increase the mortality, especially in urban areas. Which already happened during the last big heat wave in Europe in 2003 (Watkins et al., 2007).

1.1. Background

In cities, the Urban Heat Island (UHI) effect - the difference in air temperatures at the pedestrian level in cities are compared to those in the surrounded rural area which are not caused by other factors like topography or weather (Stewart, 2011) will enhance temperatures due to the physical properties and urbanization and will cause even higher temperatures in urbanized areas. The main cause of the effect is based in changes in the radiation (1) and/or energy balance (2) between rural and urban areas:

$$Q^* = K\downarrow + K\uparrow + L\downarrow + L\uparrow \tag{1}$$

$$Q^* = SH + LH + G + ANT \tag{2}$$

Where /Q*/ is the net radiation, /SH/ the sensible heat flux, /LH/ the latent heat flux and /G/ the storage flux and /ANT/ the anthropogenic heat production in the energy balance. The radiation balance exists of shortwave incoming /K↓/ and outgoing radiation /K↑/ and long wave incoming /L↓/ and outgoing radiation /L↑/.

Oke (1982) and Piringer et al. (2002) describe how the urban area influences the energy balance. Based on the meteorological knowledge of the energy balance, causes of the Urban Heat Island effect are as follows (Oke, 1982):

- The canyon geometry influences the net shortwave radiation /K*/. In the Urban Canopy Layer the incoming short wave radiation will be reflected at walls in the canyon (and partly absorbed). In this way the net albedo of urban surface will decrease, and thus this mechanism will enhance /Q*/.
- Increasing incoming long wave radiation could be caused by air pollutants. Air pollution in the atmosphere will reflect outgoing long wave radiation and will send this back to the earth surface.
- Air pollution will decrease /*K*↓/, due to reflection and absorption of shortwave radiation, but also absorbs heat at the top of the planetary boundary layer.

- The canyon geometry has a negative influence on the net long wave radiation. /L*/ will decrease by increasing long wave radiation.
- Due to reduction of the sky view factor, /L↑/ is reduced.
- The extra heat caused by humans (anthropogenic heat) leads to addition of heat to the air caused by for example traffic and air conditioning. The anthropogenic heat can increase up to 100 W/m^2 downtown (Kato and Yamaguchi, 2005), although Ronda (2012) found a value of 38 W/m^2 for the city of Rotterdam, the Netherlands.
- The presence of less vegetation and more impervious surface in urban areas decreases the evapotranspiration and decrease the turbulent flux of the latent heat.
- The /G/ is larger in the city than in rural areas due to a bigger storage capacity of building materials.

As mentioned above, the role of urban green is an important aspect by influencing the air temperatures in the city and therefore the Urban Heat Island effect (UHI). The net radiation /*Q**/ in the rural area is dominated by short wave radiation during daytime and long wave radiation at night (Christen and Vogt, 2004). The remaining energy will be absorbed by the underlying soil /*G*/ and/or will go to the air by convection of /SH/ and /LH/. Due to pervious material there is more (soil) moisture available which increases the latent heat flux. In contrast, surfaces in cities are impervious, so in urban areas the rural energy process also yields after a rainy period. However, when the moisture is evaporated, the urban environment is a source of sensible heat.

The hypothesis of mitigating the UHI during daytime is based on an increasing evapo(trans)piration rate at the cost of sensible heat. This could be achieved by using either water or green areas within a city. Some studies already assessed the influence of water bodies as strongest element in cities to effect temperature (e.g. Solcerova et al., 2012; Rinner and Hussain, 2011). Research focussed on the effect of vegetation on the city climate is done more often. However, most research is based on observational work (Andrade and Vieira, 2007; Kruger and Giovani, 2007; Steeneveld et al., 2011). Those studies presenting a significant cooling effect of urban green during daytime. Therefore, this research is a modelling research focussing on the influence of vegetation on the UHI. The knowledge of the cooling effect of urban green is often implemented in urban planning to design public spaces (Kleerekoper et al, 2011). The cooling effect of urban green, like urban forests (parks), street trees, private green in gardens and green roofs or façades has been studied by a lot of scientists (Zoulia et al., 2008; William and Timothy, 2011; Oláh, 2012).

As mentioned before, the influence of urban green on the city climate has been assessed by many scientists. However, most research has been empirical developed by analysing data from local (urban) weather stations (Andrade and Vieira, 2007; Kruger and Giovani, 2007; Steeneveld et al., 2011). Another part of the UHI research is based on modelling approaches. These modelling researches focus on existing cities and they use often remote sensing data (Owen, 1998; Hirano et al., 2004; Rinner and Hussain, 2011).

One of the observational studies is done by Steeneveld et al (2011). He discovered a relationship between the UHI magnitude and percentage of greenness in a city based on observations in the Netherlands. However, a relation between the percentage of greenness and human comfort is not found. The reason could be the higher specific humidity in cases with a high percentage of urban vegetation, which decreases the human comfort.

Several observational studies showed an effect of the vegetation type on the temperature regime in vegetated areas (Potcher et al., 2006; Jonsson, 2004). The maximum cooling effect of parks with trees is hypothesized to be reached in the late afternoon, while open grass areas reach this maximum just before sun rise (Spronken-Smith, 1994). The cause could be found in the fact that a well treed park has a lower sky view factor and therefore less long wave radiation which can be emitted during the night. While during daytime the shade of the trees cause a cooling effect by reducing the incoming shortwave radiation.

Next to the essential difference between grass fields and forests, there is an important distinction between just single trees and groups of trees. In case of a single tree, the most important effect is blocking the sun light during daytime (Andrade and Vieira, 2007). Underneath a single tree the biggest difference is caused by shortwave radiation. One tree can block 88% of shortwave radiation. Next to this, outgoing long wave is partly reflected by the crown of the tree. Due to this effect the net incoming long wave radiation under a tree is much higher compared to its surroundings. By those differences in the radiation balance, the net radiation is lower in areas under a tree.

A tree in a street canyon will act differently during daytime than a tree in an open field. A tree surrounded by buildings receives large amounts of reflected short-wave radiation from canyon walls and floor (Oke, 1982). Another big effect on a single tree caused by the urban area is the high input of long wave radiation by buildings, the crown of the tree will strengthen this process by blocking long wave outgoing radiation from the surface to the atmosphere. The last source of heat from outside the tree could develop when the air temperatures are higher than the leave temperatures. In that particular case, sensible heat will be directed to the single tree. During night-time the reduced sky view factor and the emissions of heat from surrounded buildings will lead to higher temperature under the tree.

Unfortunately, it is impossible to model the effect of single trees. Groups of trees will influence the incoming shortwave radiation more. This is caused by a reduction in the diffuse radiation. This diffuse radiation is blocked by surrounded trees. Andrade and Vieira (2007) found more often a significant temperature difference between measurements in areas with more trees and the surrounded area compared to those under only one tree. Therefore we will focus more on larger urban green areas, like grass fields and urban forests.

A next aspect which has a substantial effect on the temperature and human comfort in a city is the soil moisture content. An increased soil moisture could reduce the Diurnal Temperature Range (DTR) through enhanced evapotranspiration (Zhou, 2004). However, Spronken-Smith and Oke (1998) pointed the fact that dry parks during the day could have higher temperatures than the surrounded city. The effect of the soil moisture of grass and other types of vegetation is also mentioned by Cao et al. (2010). In that research the adverse impact of grass is shown, what is mainly resulted from the unfavourable condition of grass growth leading to large soil coverage in the study area. Also the available (soil) moisture of grass fields is mentioned. Non-irrigated areas with grass cool down faster during the night and heat up much faster at daytime. So maintenance of urban green in terms of irrigation is pointed out to be essential for 'regulating' the urban climate.

Some research is done with the aim to understand the effect the size of green areas on the air temperature. It is difficult to generalize those results of research. Zoulia et al. (2008) gives an overview of some observational researches done in this discipline. A few general conclusions could be made. In cases of larger green areas (>500m^2) one can conclude that those parks has a cooling effect on the environment. The average air temperature in vegetated areas are 0.47 °C to 5.6 °C lower than in the built environment. In other studies, green areas are sometimes warmer. During daytime, urban parks with grass, without trees and less irrigated, could cause hot spots in the city. During night-time, the parks with a high tree density are warmer. In addition, the temperature differences between vegetated areas and their urban surrounding are higher during the night. In addition, Andrade and Vieira (2007) measured higher temperatures in sunny spots in the park than shaded spots outside the vegetated areas. A relationship exists between the size of green areas and the distance the vegetation could influence the air temperature. Studies indicate that big parks (500 ha) could influence air temperature at 2 kilometres distance, while smaller parks (35 ha) have a maximum range of 1 kilometre. In general, a rule of thumb has been formulated by Spronken-Smith (1994): The influence of parks is measurable at once the width of the park.

The distribution of green in cities and the size of urban vegetation could affect the general urban climate differently (Huang et al., 2011). By studying the spatial distribution of the percentage green in cities, Huang et al. (2011) did not find a significant effect of green on the urban air temperatures during daytime. The effect of another type of vegetation and the effect during night time is not assessed. Therefore the current study focuses on the influence of urban parks with different vegetation types on the day and night time urban temperatures and human thermal comfort.

Next to temperature effects of green distribution, recent studies emphasize also the effect of greenness on the citizens health (Maas et al., 2006). Especially, vegetation areas close within a radius of 1 to 3 kilometre of a resident, has a positive effect on the human health. Another important trend in urban planning is the implementation of urban agriculture. Urbanization increases, so does the need for sufficient food increases. The opportunity to acquire locally produced food becomes more and more important (Bryld, 2003).

Temperature is a variable to measure the effect of vegetation on the city in an objective way. However, human comfort is an important parameter to discover the effect of the urban climate on the human body (Budd, 2001). Human comfort is not directly linked to temperature. Evapo(trans)piration of vegetation and soil causes a mitigation of heat in the city. Nevertheless, a too high humidity is not comfortable for human beings. Human comfort is dependent on many factors, like temperature, wind speed, relative humidity, radiation, clothing and metabolism. In our research the Wet Bulb Globe Temperature (WBGT) is used to define the human comfort. The WBGT is an index which could be used by the use of meteorological data air temperature and humidity.

Based on the prescribed literature research the main objectives of this study are summarized in the following research questions:

- To what extent does urban vegetation has an influence on the Urban Heat Island and human thermal comfort?
- What is the additional impact of environmental aspects as soil characteristics, vegetation types and urban green distribution?

As mentioned before, a lot of observational research has been done in this field. The measured data in the observational studies are not only influenced by the studied feature (urban green) but can also be influenced by other case specific aspects as topography and land use. Therefore an mesoscale meteorological model is used in our research to develop an academic city. In this way the other aspects can be erased and the pure effect of urban vegetation can be studied.

There are a few more reasons for using a mesoscale model. First, Huang et al. (2011) already used a large-eddy simulation land surface model to study the influence of green on the (urban) atmospheric boundary layer to find out the influence of vegetation on the UHI. However, this technique focuses on a particular time during daytime. Second, during our study we are investigating the development of vegetation influences on the UHI during the entire day and at the urban level.

This Msc. research is structured as follows. In the next section of this work the methodology is described. The methodology exists of different approaches to find the influence of vegetation on the UHI. The third section shows the results of the different approaches. In section 4 the results are discussed briefly, while in the last chapter some conclusions and recommendations will be given.

2. Methodology

This study is performed using the Weather Research & Forecasting (WRF) version 3.4.1. model (Skamarock et al., 2008). This model is a mesoscale model which simulates atmospheric processes on a grid scale of kilometres to hundreds of kilometres. Since the aim of this study to generate general applicable conclusions, an academic city (r=25km) is created far away from water bodies (seas or lakes) to avoid disturbing influences. Also topography, land use and soil properties are made monotous, to get a model outcome only caused by the urban green. In this section the numerical model WRF is described and the settings are explained. Next to this, the general case description and the specific research approaches are given.

2.1. Case description and model set up

The model requires input of meteorological variables and boundary conditions of global scale conditions, which are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), array 6 hours.

The UHI is most visible during hot summer days. Therefore a recent summer case from 7 to 10 July 2010 is selected. Temperatures raised up to 30 to 35 degrees in eastern Netherlands and western Germany. This in combination with a low background wind between 1 and 4 m/s at 1.5 m height from the south, make those days ideal for studying this topic.

In order to set up an academic simulation, information about the land surface such as land-use, soil type and topography - are simplified. The rural environment is set to grass to erase the influence of land use heterogeneity. Another important aspect which effects the development of the air temperature is the soil type and soil moisture. The most common type in the area of the city is loam. By using an iterative process we found a stable soil moisture content 0.27 m^3 m^{-3}, which is used for the vegetated urban areas.

The simulation is started on 6 July 2010 at 00:00 UTC. At this start point the values of air temperature, humidity, components of the wind speed, soil temperature, soil humidity are calculated in the vertical and horizontal direction with the aid of the ECMWF.

The simulation stars 6 July 2013, and has a spin-up period of 1 day is chosen. This means that the output of 6 July 2010 is not analysed, so the studied output is from 8 till 10 July 2010 (Figure 2), and the model output is provided hourly.

To simulate the process of the mesoscale situation, the WRF model is configured using 2 domains (Table 1). These domains are divided by grids. The outermost domain exists of 32x32 grid cells of 25 km x 25 km. Hence, the total size of the WRF model is 800 km. But to analyse the city climate, three smaller domains are established: 60x60 grid cells of 5 km x 5 km; 100x100 grid cells of 1 km x 1 km. The centre of the domains is situated at (52N 7.5E). To calculate the vertical component of the atmospheric processes 35 layers are used with 9 levels under 1000m. The lowest level is located at 22m.

2.2. Parameterization Schemes

Within the WRF model, parameterisations are used for processes smaller than the grid scale, which cannot be calculated by the WRF model (Table 2). The used parameterizations are mentioned in table 2. To calculate the vertical division of fluxes of long wave radiation in the atmosphere the CAM Scheme is implemented in de model (Collins et al., 2006). The Cam Scheme allows for aerosols and trace gases and the Dudhia scheme is chosen for simple downward integration allowing efficiently for clouds and clear-sky absorption and scattering. For the implementation of microphysics, the WSM 3-class simple ice scheme has been employed (Hong et al., 2004).

Next to these parameterisations, the Noah land surface model (Ek et al, 2003) is used to estimate the surface fluxes of the sensible and latent heat. The Noah land surface model is provided with a bulk parameterisation for the urban area. The used model is the single-layer urban canopy model (SLUCM). The model assumes an infinite street canyon divided in three components: the roof, the wall of both side of the canyon and the road (Kusaka et al., 2001). The energy balance is calculated for each of these components, as a function of the incoming fluxes of short wave and long wave radiation, and the temperature at the lowest model level. The convections scheme which is used in the WRF model setup is a technique used in numerical modelling to predict the collective effects of convective clouds that may exist within a single grid element as a function of larger-scale processes and conditions (Kain-Fritsch)

Since the phenomenon that we study is a typical boundary layer phenomenon, at least two different boundary layer schemes (MYJ and YSU) are used in order to evaluate the model sensitivity to the selected scheme.

All the urban areas are treated as high densely built residences. Due to the enormous variation of urban morphology in different European cities, the values of a typical American city are implemented in the urban parameterizations (Table 3). Next to the urban morphology the land use is another important aspect with respect influence on the urban climate. An equilibrium of soil temperature and soil moisture is found to avoid heating and drying of the soil which influences the air temperature rigorously. After several iterative runs, the soil temperatures in the urban area were set to 295K, 290K and 288K for the soil surface, the first layer and the second layer respectively. The features of the lowest layer did not change during the four simulation days. An equilibrium of the soil moisture around 0.10 m^3 m^{-3} is found over all layers in the city.

We use four approaches to analyse the effect of vegetation on the UHI and human comfort. The way of analyses starts in a more theoretical approach, and it is becoming more practical later on in our study. First two boundary-layer (YSU & MYJ) schemes are analysed, afterwards the influence of different vegetation types and soil moisture within the park are discussed and lastly the distribution of vegetation in the city. Table 4 gives a clear overview. In this study we address four research topics of the different runs and their specific characteristics.

2.3. Boundary Layer scheme

Because our study is about a typical boundary layer phenomenon, it is important to know what the effect is of the scheme choice on the process. Therefore, we analysed the sensitivity of two different boundary-layer schemes, MYJ and YSU, on the model results temperatures.

The Weather Research and Forecasting (WRF) model offers different boundary layers schemes. In our case the eta implementation of 1.5-order local closure of Mellor and Yamada by Janjic (MYJ) (Mellor and Tetsuji, 1974) and the Yonsei University (YSU) (Hong et al., 2006) non-local scheme will be compared. A non-local scheme only accounts for vertical transport from neighbouring grid cells.

According to literature the YSU and MYJ are giving an underestimation of the heat transfer between surface and atmosphere than MYJ (Pagowski, 2004). However, MYJ underestimates the heat transfer much more than the YSU scheme. Therefore, in convective conditions with weak wind, the YSU scheme develops a Boundary Layer twice as deep as the MYJ. During the night the MYJ is the most decoupled system from the surface. For this reason, the heat transfer between surface and atmosphere will be lower than in the YSU scheme.

To analyse the sensitivity of the boundary layer scheme, four runs (MYJ_G, YSU_G, MYJ_C, YSU_C) will be done. The first two runs show the effect of the MYJ and YSU scheme in a grassland area, while MYC_C and YSU_C mapping the effect of both boundary layer schemes in an urbanized area. At the end, the boundary layer scheme which represent the best diurnal UHI profile will be chosen for the next runs.

2.4. Vegetation

After the runs with two different boundary layer schemes, the runs in WRF analysing the vegetation are the second analysed effect. Based on literature research, it is known that grass and trees have a different effect on the city temperature. It is hypothesized that urban parks with trees will reach the cooling effect in the late afternoon, while large grass fields will reach the lowest temperatures in the early morning. To investigate this hypothesis we developed a central park in WRF. At first, a run with a central grass field will be studied. By changing 25% of the circular city to grassland, the effect of a big central park on the temperature and WBGT is analysed. The land-use type in WRF was set to 7 to simulate the properties of a grassland. Second, the effect of a mixed forest is case of study. These two runs are called: YSU_G_SM27_1P and YSU_T_SM27_1P, respectively. The aim is to analyse the difference of temperature, UHI and thermal comfort between different types of vegetation, by changing the land use of a central park in WRF to grassland (land use type 7) and mixed forest (land use type 15).

However, the possibility to implement a mixed forest in the WRF model exists, but the roughness sublayer/forest canopy is not part of it. WRF develops the temperature profile by interpolation between the lowest eta-level and the temperatures at the surface. Changing the land use to mixed forest only, effects the surface temperature by the albedo and roughness length. The output of the WRF model does not show a clear difference of temperature between an open grass field and a forested park.

For a more realistic approach of the temperature at 2 meter in the park's canopy, we used a research done by de Ridder (2009) to approach the temperature profile in a pine forest by using a modified Monin-Obukhov surface layer similarity theory (3).

$$\theta(z) - \theta_0 = \frac{\theta_*}{k}[\ln\left(\frac{z}{z_{0H}}\right) - \psi_H\left(\frac{z}{L}\right) + \psi_H\left(\frac{z_{0H}}{L}\right) + \psi_H^*\left(\frac{z}{L}, \frac{z}{z_*}\right)] \quad (3)$$

where z is the height above the displacement height, z_* is the roughness sublayer height above the displacement height, θ_0 is the temperature at z_{0H}, k is the von karman constant (0.4), L is the Monin Obukhov Length and ψ_M, ψ_H are the integrated stability functions. The last part of the equation accounts for the influence of the roughness sublayer on the temperature profile relationships (4).

$$\psi_H^*\left(\frac{z}{L}, \frac{z}{z_*}\right) \approx \phi_H\left[\left(1 + \frac{\nu}{\frac{\mu z}{z_*}}\right)\frac{z}{L}\right]\frac{1}{\lambda}\ln\,(1 + \frac{\lambda}{\frac{\mu z}{z_*}})e^{-\mu z/z_*} \quad (4)$$

Where $\mu \approx 0.95$, $\nu = 0.5$ and $\lambda = 1.5$ are given by de Ridder (2009) and ϕ_H is the stability function.

To develop an approximation of the 2 meter temperature in the forest canopy, a number of assumptions to solve the equation has been made. At first the canopy height (z) in the model is assumed to be 20 meters (de Ridder, 2009), the displacement height in the forest to 0.7z (Grimmond and Oke, 1998), and that means a z_* of 34m. The roughness length stays the same as given in the WRF model: 0.35 m. From this the roughness length for heat (z_{0H}) can be calculated by using $kB^{-1} = \ln(z_0/z_{0H})$ (Blümel, 1998). Where kB^{-1} is equal to 2 for dense vegetated forests. Using this equation and assumptions, the z_{0H} will be set to 2 meters.

2.5. Soil moisture

Soil moisture is another essential parameter of urban parks to influence the air temperature in cities. We hypothesized that more soil moisture could cool down the park's surroundings during daytime. Soil moisture could be regulated easily by human beings due to watering of urban vegetation. Therefore the soil water content of the urban central park in the model is set to two soil moisture extreme values: wilting point (0.066) end the field capacity (0.329) of a loamy soil. This forms runs YSU_G_SM6.6_1P, YSU_G_SM32.9_1P, YSU_T_SM6.6_1P and YSU_T_SM32.9_1P.

2.6. Spatial Distribution

The distribution and percentage of the green area of cities is an important factor by influencing the UHI. Huang et al. (2011) used an approach with a systematic vegetation cover of 14%. Compared to European cities, this value is too low. In Amsterdam 24.2 % of the city is covered by vegetation (forest, recreation, agriculture) (Amsterdam.info, 2012) almost 18% is forestland, another 11.5% is devoted to recreation areas, and more than 5% is used for farming (Green Berlin, 2012). Based on this knowledge the percentage of green in the academic city is set to 25% of the total size of the city. Cao et al. (2010) already indicated that park size is non-linearly correlated to the park cooling intensity (PCI).

Next to the size, some conclusions were made about the park shape. Irregular and belt shaped parks tend to have a lower cooling effect than parks of a regular (round or square) shape . However, by the low spatial resolution of the ASTER LST data this effect could be underestimated.

To investigate the effect of park size and park shape based on urban planning ideas, the percentage of green is distributed over the city in different ways. The size effect is studied by splitting up the urban vegetation into a different amount of parks of different sizes. However, the percentage of green is consequently set to 25%.

The next step is to discover the effect of park shape. Two main motivations are based to create a green network of vegetation within a city. A multifunctional function of a green environment and an ecological function to connect important green ecological areas (Hoogstra and Molenaar, 2000). Based on these ideas, the effect of green corridors on the urban climate will be studied in the YSU_G_SM27_COR and the YSU_T_SM27_COR run.

At the end the following runs will be done to investigate the effect of distribution on the city temperature:

- YSU_G_SM27_2PH shows the effect of two urban grass fields perpendicular on the wind direction.
- YSU_G_SM27_2PV shows the effect of two urban grass fields parallel to the wind direction.
- YSU_G_SM27_4P run shows the effect of four equal distributed urban grass parks.
- YSU_G_SM27_COR figures out the effect of green grass corridors.
- YSU_G_SM27_INT uses green as percentage of a urban grid cell. By changing the proportion green of every urban grid cell from 0% to 100% in steps of 10%, the expectation is that a relationship between greenness and UHI could be found. Thus the YSU_G_SM27_INT-run can be divided in 11 sub-runs. In the WRF settings the type of vegetation is determined by grass (7) and forest (15) in the land use table.
- YSU_T_SM27_2PH shows the effect of two urban forested parks perpendicular on the wind direction.
- YSU_T_SM27_2PV shows the effect of two urban forested parks parallel to the wind direction.
- YSU_T_SM27_4P run shows the effect of four equal distributed urban forested parks.
- YSU_T_SM27_COR figures out the effect of green forested corridors.

2.7. Analyses

At first a sensitivity analysis will be done with regard to the boundary layer scheme. After the analysis the boundary layer scheme which shows the most ideal diurnal cycle of the UHI according to literature will be selected for the next analysis. Secondly, the effect of different kinds of vegetation and soil moisture will be studied. To analyse the effect of each case, the temperature change at each time will be studied. Next to the extremes, we will have a method by estimating the average temperature over the entire city and the anomaly will be compared to the base run. Also we compare how much per cent of the city will be influenced by the green areas, the temperature change on the edge of the vegetation.

2.8. Human comfort

Because the temperature/UHI is not the main indicator of thermal comfort. Human comfort is governed by more variables like temperature, humidity, air movement, radiant temperature, clothing (Havenith, 1999), and metabolic rate. However, the human comfort's dependents on a lot of different variables which are not an available input parameter. Therefore the Wet Bulb Globe Temperature (WBGT) is the most convenient parameter in our research to make a reliable assumption of the human comfort based on only two meteorological variables:

$$WBGT = 0.567Ta + 0.393e + 3.94 \quad (3)$$

Where Ta is the air temperature (°C) and e is the water vapour pressure (hPa). However, this method is an approximation of the human comfort and the subjective experience depend largely on clothing and personal activity.

The WBGT is also used to set up regulations for working men with respect to heat stress (WBGT,ISO 7243, 1989). A general rule of thumb for the general public is as follows: a WBGT < 27.7°C represents conditions without heat stress (Steeneveld et al., 2011). For 27.7°C < WBGT < 32.2°C the heat stress increases, and for WBGT > 32.2°C great heat stress danger occurs. Public events will be cancelled when the WBGT > 31°C. Physical training (e.g., sports) is not advised for WBGT > 29.4°C.

3. Results

In this chapter the results of the modelling experiments will be summarized. At first some general results will be described. In the sections 6.2. to 6.5. the results of the four different approaches will be explained.

3.1. Model evaluation

In order to validate the model, we first evaluate against data for Temperature, humidity and wind. The magnitude of the UHI is determined by using two different spots: One in the city centre and the other far away from the city's influences, neither downwind nor upwind. The WRF results show an Urban Heat Island Effect which reaches ∽ 5 K in the early morning around sunrise and 1 degrees in the early afternoon (Figure 3). The graph is similar to the typical diurnal cycle described by Oke (1982).

According to the observations of existing weather stations nearby our academic city, the UHI of Bochum is around 5 degrees (24 °C - 19 °C) and the UHI of Utrecht amounts to 3 degrees (21 °C - 18 °C) at midnight of the 9th July 2010 (Weather Underground, 2008). Theory and observations support our findings, and give us confidence in the model results.

Hence we conclude that another important aspect of the modelled UHI is the suppressed diurnal cycle of temperature in the city: The Diurnal Temperature Range (DTR). Due to more heat storage in the urban area at daytime, more heat could be released at night, which causes higher temperatures during nightly hours. The difference in the temperature's diurnal cycle varies from 11°C in rural areas up to 16°C in the city.

In addition to temperature, the wind speed is influenced by the city. Especially at night, the wind speed is consistently higher in rural areas in case of using the MYJ scheme. The wind for MYJ gives 2.5 m/s, while YSU has a wind speed of 4 m/s. During the day the wind speed is fluctuating much more, but at average there is more wind outside the city (1.0 m/s). Also the delay of the wind's slowing down in urban areas in the early evening.

The difference in day and night is caused by the presence of buoyancy. During daytime the atmosphere is unstable which causes the exchange of air parcels between upper air and air near the surface. The land use type (grass or city) is not affecting the buoyancy strongly. At night the degree of turbulence is mainly caused by wind shear instead of buoyancy. The city has a higher roughness length which is responsible for a lower shear in urban areas. Also the u* is higher in the urban area. Due to the higher roughness length in the city, more mechanical turbulence is produced. A delay in decreasing of u* in the city is clearly visible in the afternoon.

These general results give us confidence in the model results to continue our study on the boundary layer scheme, vegetation type, soil moisture and vegetation distribution.

3.2. Boundary Layer scheme

As described in section 2.3. different model responses are generated by the different boundary layer schemes.

The first major observed difference is the difference in boundary layer growth. The MUY model develops faster and also the boundary layer height is 500 meters higher than in case of the YSU scheme. At night the YSU produces a more stable atmosphere than YSU, while the instability is higher during daytime. This effect is also clearly visible in heat transfer in the bottom part of the boundary layer (Figure 1). The YSU is responsible for a fast development of the boundary layer in the early morning hours. The heating of the upper atmospheric layers is therefore higher. However, in the afternoon temperature in the entire MYJ boundary layer is higher. At night both boundary layer conditions cause a stable boundary layer. YSU generates a more stable layer compared to the MYJ. In rural areas this means lower temperatures, while in the city release of heat becomes more difficult.

Except the temperature differences in the vertical direction, a horizontal difference on the 2 meter level caused by the boundary layer scheme is also visible. Due to more turbulent circumstances in the MYJ scheme, a bigger urban plume is generated at night. Temperatures downwind of the city are 3 degrees higher for almost 25 kilometre. The same effect is shown in the contour plots of the WBGT.

By adding a city to the grassland the largest temperature effect is in the YSU_C case (Figure 2). During daytime the temperatures are at average 8.5 degrees higher compared to the grassland case. At night a more stable YSU-boundary layer causes a relatively smaller temperature change.

The wind speed is higher in cases without urban areas. Also the effect of the boundary layer scheme on the wind speed is significant. The YSU scheme is responsible for lower wind speeds in rural as well as in urban environments. The humidity in the air is another important meteorological variable which is influenced. MYJ causes a higher value for the mixing ratio in the air in the city and in the rural areas.

The most convenient boundary layer scheme is chosen based on the effect on the most important variable in this study: the diurnal UHI (Figure 3). The YSU scheme gives the best representation of the development of the diurnal UHI according to the one given by Oke (1982). Therefore, this boundary layer condition will be used in our further research.

3.3. Vegetation

As mentioned before, the vegetation type plays an important role in the consequence of urban vegetation in relation to urban climate. This section shows the influence of different vegetation types in a central park. Therefore, we set the vegetation to grass and trees.

Figure 4 shows the comparison of the diurnal cycle of temperature and the temperature change caused by the introduction of a park with grass. In the mentioned figure it is clearly visible that the park has the strongest cooling effect during the nightly hours (2.0°C -2.5°C). The most pronounced temperature change occurs around sunrise and sunset. This can be explained by the fact that grass cools faster in the early evening, and the city cannot release its heat that quickly. In the early morning the converse effect takes place: quicker heating of the grass field leads to a positive temperature difference. During the day, the cooling effect still exists and reaches its maximum just before sun set.

In order to explain the temperature changes, we study the energy balance at three different spots (Figure 5). In the park a slightly negative /SH/, a /LH/ around 0 and slightly positive /G/ could be found at night. At the same time the energy balance components in the city are positive for /SH/, nearly 0 for /LH/ and the soil flux becomes positive. While the grass field cools down, the city is still heating up. In combination with wind speeds around 3.5 m/s, cool air from above the park is advected towards the city, and causes a cooling effect at the downwind park edge.

The urban energy balances in Figure 5 are dealing with a higher sensible heat flux and a lower /LH/ than the energy balance within the central park. Less water is available to evaporate in the urban area and more energy could be used to heat up the air. The soil heat flux is also more extreme, during the day more heat could be absorbed by the urban materials, while the energy will be released during night-time. The energy balances upwind and downwind are nearly the same. However, during night-time a small difference in the soil flux and sensible heat flux is visible. The crosssection in figure 6a shows the 2m temperature from the southeast to the northwest around 04:00 at night. Relatively cold rural air from the south east is blown towards the city. The air temperature increases 4 degrees when it is entering the city. Than it crosses the border of the central park and the temperature drops down more than 1 degree. So the air which is entering the spot on the north-western part of the park is a 3 degrees warmer compared to the air which enters the southern urban area. This causes a more unstable situation of the atmosphere in front of the park (Figure 6b). The air in the southeast could heat up even more. As a consequence the soil flux and the sensible heat flux are slightly higher in the south-eastern part of the city.

A spatial effect of a central grass field is shown in figure 7 (Default). In case of YSU_G_SM27_1P temperatures downwind of the city are 1 to 3 degrees lower than the reference YSU_C run. The park itself functions as a cooling island, where temperatures could drop down 7 degrees compared to the YSU_C run. The influence of the cooling plume (>0.5°C) of the central park could reach a distance up to 25 kilometres during the moment of strongest cooling.

As mentioned earlier, a forest has another effect on temperature regime than a grass field. However, WRF could not create a realistic approximation of the temperatures under trees. Therefore the equations of de Ridder (2009) were used to develop an approximation of the temperature profile within the forested canopy. However, corrections of the resulting temperatures were not feasible. Temperatures within the canopy were way too high and not reasonable to implement in our study. The reason for this is that z and z* have to be larger than d. For a forest with a canopy height of 20 meters and a displacement height of 14 meters, it is necessary to use negative z/z* values to calculate the temperature at a 2 meters level. However, the approximation of de Ridder (2009) is calibrated for $0.2<z/z^*<3$ en $-5<z/L<1$. In this way it is impossible to achieve a correct value for the 2 meters temperature.

3.4. Soil moisture

To investigate the effect of human maintenance in terms of irrigation, the soil water content of the urban central grass field is set to the wilting point (0.066 m^3/m^3) end the field capacity

(0.329 m^3/m^3) of a loamy soil. We used a threshold of 0.1°C as minimal temperature change during this research. Note that the runs of different soil moisture contents of a central forest are not used (see previous section).

Figure 7 shows the spatial effect of different values of the soil moisture content. Decreasing/increasing the soil moisture of the park to wilting point (YSU_G_SM6.6_1P) or field capacity (YSU_G_SM6.6_1P), shows a big influence on the temperatures in the central park. In all cases the cooling plume during night-time reaches more than 25km outside the city boundaries. The strongest cooling effect could be found downwind at the edge of the central grass field (-6˚C/-7˚C). During daytime the cooling effect is less, but still visible in all cases. However, a well watered park depicts lower temperatures in the afternoon. The cause could be found in the energy balances of both cases. Due to more presence of water, less solar radiation is turned into sensible heat, which is the cause of decreasing air temperatures. In a park with the soil moisture content set to wilting point, shows almost no temperature difference compared to high densely built city.

Looking at a temporal scale, neither a cooling nor a warming effect due to a central park is visible downwind at the city edge (Figure 8). Closer to the park figure 8 depict a more significant effect. The diurnal temperature range at the edge of the park is weakening in case of a higher soil moisture contents. A dry park indicates a 2 degrees cooler urban spot downwind of the park edge in comparison to a relatively wet park during night time. The main reason for this is the fact that a humid soil could store more heat, which is released during the night. In the afternoon the opposite occurs: Due to a higher value of the soil moisture, more water is available to evaporate. This generates an increase of the latent heat during the day, which suppresses air temperature. Well watered grass fields are 24 hours responsible for a cooling effect close to the downwind side of the park. Despite the stronger cooling effect of a dry park at night, a dry park at wilting point has also a warming effect. Temperatures at daytime are between 0.1 and 0.5 degrees Celsius higher than the run without vegetation.

3.5. Spatial Distribution

The next analysed aspect is the effect of the spatial distribution of urban green on the UHI. By dividing the amount of green over different urban parks four runs were set up: two runs with a city with 2 parks parallel and perpendicular to the wind direction, with 4 parks and a run with green corridors (Figure 9).

Spatially the effect of different distributed parks is visible in Figure 10. The strongest cooling effect at the edge of the park is found YSU_G_SM27_2PV and YSU_G_SM27_COR. In these runs the urban area at the park edge could cool down up to 3 degrees at night. During the day nearly the same spots experience the strongest cooling effect.

Figure 11 shows the percentage of the city that experiences a cooling/warming effect of more than 0.1°C. The minimum/maximum peeks of warming and cooling occur at the same time. However, next to the constant diurnal cycle of temperature change, there exists a clear difference between the runs. The cooling effect is slightly increasing with a more equal distribution of vegetation over the city. Around 30% of the city cools due to a compact central park, while by using green corridors 50% of the city is cooled. Looking to the extremes during night-time give a good view on the effect of park distribution. The cooling effect of green corridors (60%) is almost doubled compared to the 1 park run (35%). Two parks have a nightly extreme of 45% and 4 parks around 59%.

In the second line of figure 11, the more extreme temperature changes (>°0.5C) are plotted. In case of compact parks, the temperature effect stays more or less constant during day and night. In case of more equally spread parks, the diurnal influence is clearer visible. Especially during daytime better spread urban green causes a higher percentage of cooling in the city. However, during night the cooling effect of more than 0.5°C in more significant in a bigger/compact park.

In a world of increasing urbanization, it is important for human health to get easily access to urban green at short distances. As a next step the vegetation is equally spread over the city. By increasing the vegetation fraction in the urban grid cells by 10%, we aimed to find a correlation between maximum UHI and percentage of greenness. As shown in figure 12 the model found a decreasing UHI by implementing more vegetation in the urban grid cells of the model. It fits between the 95-percentile line and the median found by an observational study of Steeneveld et al. (2011) in cities in the Netherlands. Because comparison with observations gives us confidence in the model results, we tried to discover more effects on temperature and WBGT. A city without any urban vegetation has a 4 degrees higher WBGT compared to the rural environment. By increasing the amount of vegetation, the maximum reached WBGT difference becomes less. The decreasing temperature UHI graph in relation to greenness is much steeper compared to the WBGT UHI. This is caused by the counterbalancing effect of the humidity of the air, which increases with the greenness.

3.6. Human Comfort

A last objective during our study is to discover how urban vegetation influences human comfort. A difference between the air temperature and the WBGT strongly depends on the soil moisture content (Figure 13). A relatively dry soil always lowers the perceived cooling effect during the night close to the park (Figure 13a). While the cooling effect in air temperature is around 8 degrees, the perceived cooling is only 6˚C. However, during daytime the warming effect of a dry soil is slightly weakened in the WBGT by the lack of humidity.

Parks with a wet soil are responsible for a WBGT which is always around 2 degrees higher than the air temperature (Figure 13b). However, the cooling effect in air temperature switched into a warming effect in the perceived temperature during the day. While air temperatures drop down 1 degree due to a grass field with a high soil moisture content, the WBGT will increase to values up to 1,5 degrees higher than in the city run without parks.

In order to show the influence on temperature and WBGT per hour in cases with different distributed urban green, histograms are made (Figure 14). The figure shows the average temperature and WBGT change over the city per time step. It is found that the more distributed the green areas are, the more hours a day the city experiences a more extreme cooling effect. The WBGT histograms show also some warmer hours, which is caused by more humidity in the air. Also for the WBGT-values counts that the more spread vegetation is, the less the number of warming hours.

4. Discussion

In this section the strengths and weaknesses of our study will be discussed. First in general, and second per researched subject.

Previous studies found already the existence of a cooling effect of urban vegetation on the city climate (Huang et al., 2011). The results of our study match with these findings. However, our results indicate a less discussed warming effect of air temperature during the day in case of dry grasslands. The soil moisture is an important aspect which influences the UHI. The higher the park's soil moisture, the larger the cooling effect during daytime and the larger the urban plume. Extreme low soil moisture contents could even cause slightly higher temperatures during the day which is also mentioned by Spronken-Smith and Oke (1998) and Cao et al. (2010). Essential is to point out the soil type: Another soil type could change the soil moisture capacity, and therefore the temperature effect on the city.

Also vegetation type is an important aspect to influence the city climate. In recent studies the effect of different kinds of vegetation is underexposed (Huang et al.,2011). In our case we aim to approach the effect of trees on the 2 meter temperature. The diurnal cycle of temperatures in a forested park should show an attenuated shape compared to grasslands (Potcher et al., 2006). However, the right approximation is not found to simulate the temperature profile in the forest canopy. The used correction of de Ridder (2009) did not produce reliable temperatures. Future research could develop a way to convert WRF data to values of atmospheric variables underneath the canopy.

Looking at a more spatial scale, most studies are focussed on the effect of vegetation on their close surroundings (Andrade and Vieira, 2007; Potcher et al., 2006; Spronken-Smith and, Oke, 1998). The added value of our study results, shows the effect on a bigger part of the city. The wind is responsible for transportation of mostly cool air above the park to parts downwind. The size of the so called urban plume is mainly influenced by the wind speed. In our case an urban plume up to 50 kilometres is registered during wind speeds from 0.5 to 6.0 m/s. Lower wind speeds will reduce the cooling plume of the park, and could create an intense local cooling effect. Also changing the roughness of the surface could cause a different plume.

The green distribution is another important factor which influences the temperatures in the city. Huang et al. (2011) already discovered the increasing cooling effect in cases of more equally spread vegetation. Our mesoscale modelling results confirm that smaller parks influence a higher percentage of the city. However, different situated smaller parks could create another effect. It is important to study the effect of the park location in more ways.

To discover the impact of percentage urban green on the maximum UHI, Steeneveld et al. (2011) developed a correlation diagram between urban greenness and the effect on the urban heat island effect in Dutch cities. In our modelling research, the greenness in the entire city was changed equally. However, to develop a more realistic approximation, greenness should decrease from the city centre towards the edge.

The wet bulb globe temperature is used to estimate the human comfort. However, the human body experiences more parameters which affect the human comfort. The WBGT only uses air temperature and humidity to give an indication. Other meteorological variables like radiation and air movement are not taken into account. Using the Physiological Temperature (PET) could give a more reliable approach of the way people experience certain circumstances, because next to meteorological indices, human factors are taken into account (Höppe. 1999).

The use of a mesoscale model itself has some negative sides with respect to small scale analyses. Because of the use of grid cells (smallest 1kmx1km) the model does not give a good view on the temperature close to the park where the gradient is the largest. Also the microscale level is impossible to model by WRF, such as single trees and the green space along the road.

5. Conclusions

In this study the influence of urban vegetation on the Urban Heat Island (UHI) and human thermal comfort is studied by a modelling approach of an idealized city and various vegetation types, park distribution and soil moisture contents. By using a mesoscale model the influence of vegetation type, soil moisture and urban green distribution is investigated. In general the results show a decreasing influence with an increasing distance from the park.

At first, the boundary layer sensitivity analysis shows us that the main difference between the studied MYJ and the YSU scheme in UHI. At night the YSU shows a larger temperature difference between grass and city land use. The heating of the atmosphere is faster in case of the MYJ scheme. The YSU scheme models the strength of the resulting UHI is higher due to a more stable boundary at night, and a larger heat exchange during the day.

In the discipline of urban design it is commonly accepted that urban green decreases temperatures during day and night. However, it is important to note that dry, non-irrigated grass fields enlarge the diurnal temperature cycle. Our study shows that a low soil moisture content could even increase air temperatures close to the park during daytime with 0,5˚C. In the same way, well watered vegetation attenuates the diurnal cycle. A higher soil moisture content will decrease the air temperatures (-1,0˚C) close to the park, but is responsible for increasing values (+1,5˚C) of the WBGT during daytime. A similar mitigation effect is found during the night. This counterbalancing effect of humidity needs further research to find an optimal way to irrigate urban parks and to improve the human comfort.

In addition, the type of vegetation plays another important role in the way parks could cool or warm their surroundings (Potcher et al, 2006). In this research we aimed to approach a reliable temperature profile in forest canopy. However, this is not included in WRF and research about this topic to approach the atmospheric conditions beneath the canopy are rare.

A next analyzed aspect is the distribution of city parks. Our study shows that the more vegetation is spread over the city, the higher the percentage of urban area is influenced in terms of temperature and human comfort. On the other hand, one large area of urban vegetation has a more intense effect on the temperatures within the city.

Our results give an indication of possible effects of vegetation on city temperatures. The outcomes of this research are not directly applicable in every random city, because the surrounding in the model is made homogenous. In reality the topography, soil characteristics and vegetation are more various. This could influence the effect of vegetation on the temperatures and Urban heat island differently in every single case. So for example in reality it is possible that a more strategic situated, but a lower percentage of urban green could have a larger effect on city temperatures than a central park. Therefore, it is important to discover the precise effect of urban green in every specific situation before the application by urban planners.

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Annexes Tables

Table1: Spatial settings of the domains Settings of the SLUCM.

	# of gridcells	Size of gridcells [km]	Timestep [s]
Domain 1	32x32	25x25	180
Domain 2	60x60	5x5	36
Domain 3	100x100	1x1	7

Table 2: Settings of the model parameterizations

Surface physics		Unified Noah land-surface model	
Urban scheme		Single layer UCM (SLUCM)	
Microphysics		WSM 3-class	
Longwave radiation		Cam scheme	
Short wave radiation		Dudhia scheme	
Cumulus option		Grell-Devenyi ensemble scheme	
6^{th}-order numerical diffusion		ON but prohibit up-gradient diffusion	
Non-dimensional rate		0.12	
Boundary-layer option		MYJ	YSU
Surface-layer option		Monin-Obukhov scheme	Monin-Obukhov scheme
Eddy coefficient option		Constant horizontal dif. ($300 m^2/s$)	Horizontal Smagorinsky first order closure

Table 3: Settings of the model parameterizations

Urban Parameters	**Value**
Roof level	7.5 m
Standard deviation of the roof height	3.0 m
Rood width	10.0 m
Road width	9.4 m
Anthropogenic heat	1
Fraction of the urban landscape which does not have natural vegetation	1.0
Heat capacity of roof	1.0 E6 J m-^{3}K^{-1}
Heat capacity of building wall	1.0 E6 J m-^{3}K^{-1}
Heat capacity of ground/road	1.4 E6 J m-^{3}K^{-1}
Thermal conductivity of roof	0.67 J s^{-1}K^{-1}
Thermal conductivity of building wall	0.67 J s^{-1}K^{-1}
Thermal conductivity of ground/road	0.4004 J s^{-1}K^{-1}
Surface albedo of roof	0.2
Surface albedo of building wall	0.2
Surface albedo of ground/road	0.2
Surface emissivity of roof	0.9
Surface emissivity of building wall	0.9
Surface emissivity of ground/road	0.95

Table 4: Overview of the different runs (runs marked by a * were not feasible, see chapter 3.3.)

	Run	BL-scheme	Vegetation Park	Soil moisture park [m^3/m^3]	Urban Green distribution
Boundary Layer Scheme	**MYJ_G**	MYJ	all grass	-	-
	YSU_G	YSU	all grass	-	-
	MYJ_C	MYJ	City	-	-
	YSU_C	YSU	City	-	-
Soil Moisture	**YSU_G_SM27_1P**	YSU	Grass	0.27	1 central park
	YSU_G_SM6.6_1P	YSU	Grass	0.066	1 central park
	YSU_G_SM32.9_1P	YSU	Grass	0.329	1 central park
	***YSU_T_SM27_1P**	YSU	Trees	0.27	1 central park
	***YSU_T_SM6.6_1P**	YSU	Trees	0.066	1 central park
	***YSU_T_SM32.9_1P**	YSU	Trees	0.329	1 central park
Park Distribution	**YSU_G_SM27_2PH**	YSU	Grass	0.27	2 parks (E-W)
	YSU_G_SM27_2PV	YSU	Grass	0.27	2 parks (N-S)
	YSU_G_SM27_4P	YSU	Grass	0.27	4 parks
	YSU_G_SM27_COR	YSU	Grass	0.27	Corridors
	***YSU_G_SM27_INT**	YSU	Grass	0.27	integrated green (0-100%)
	***YSU_T_SM27_2PH**	YSU	Trees	0.27	2 parks (E-W)
	***YSU_T_SM27_2PV**	YSU	Trees	0.27	2 parks (N-S)
	***YSU_T_SM27_4P**	YSU	Trees	0.27	4 parks
	***YSU_T_SM27_COR**	YSU	Trees	0.27	Corridors
	***YSU_T_SM27_INT**	YSU	Trees	0.27	integrated green (0-100%)

Annexes Figures

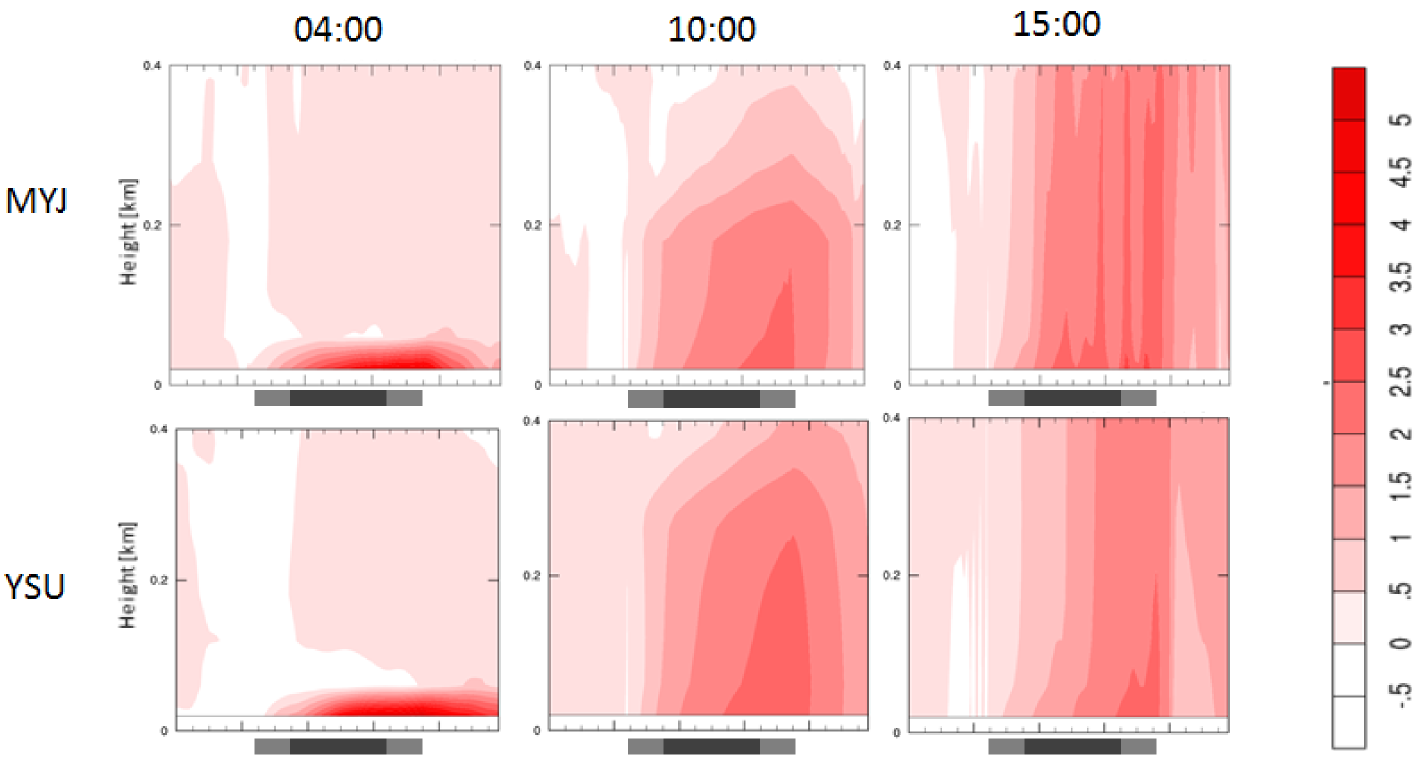


Figure 1: Vertical cross section through the third domain showing the temperature change for MYJ_C (top line) and YSU_C (bottom line). Colour bars are in degrees Celsius. Grey bars show the position of the city.

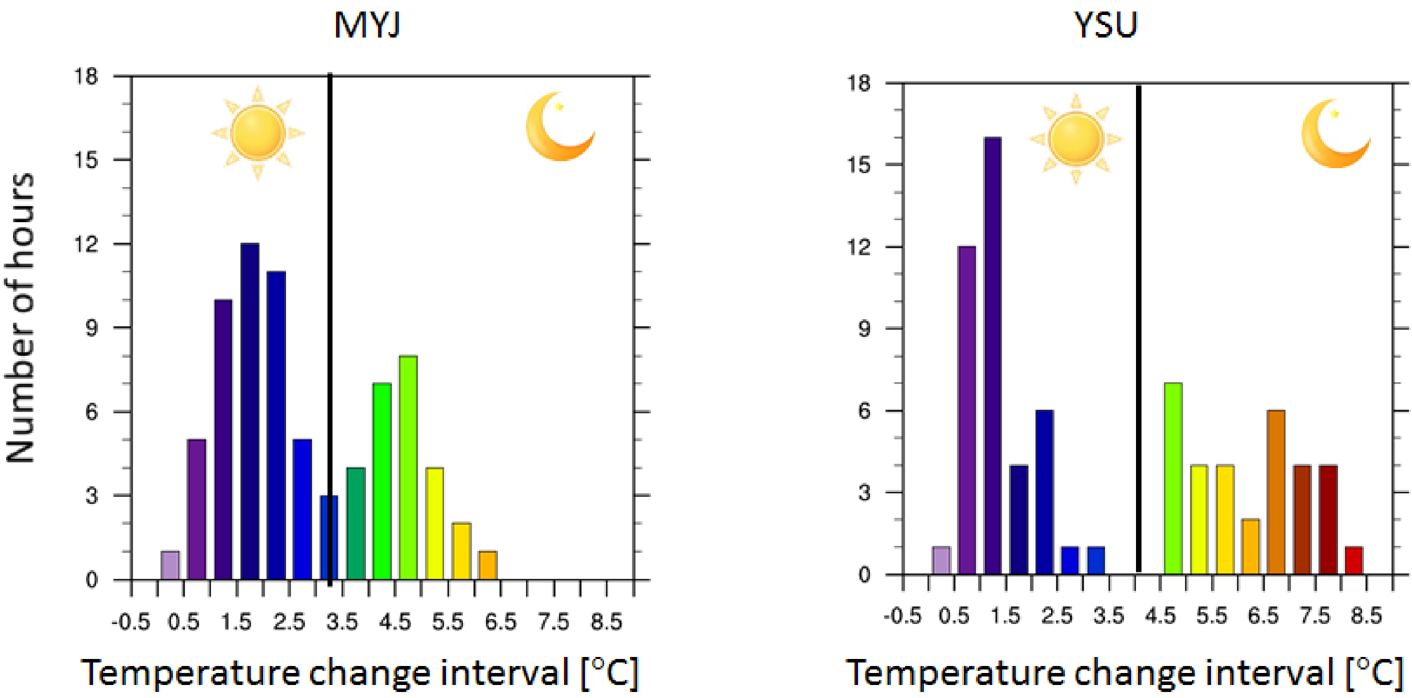


Figure 2: Frequencies of UHI. Data only from the area where the change is <-0.5 or >0.5 (average over the urban area for each time step). Left for MYJ, right for YSU.

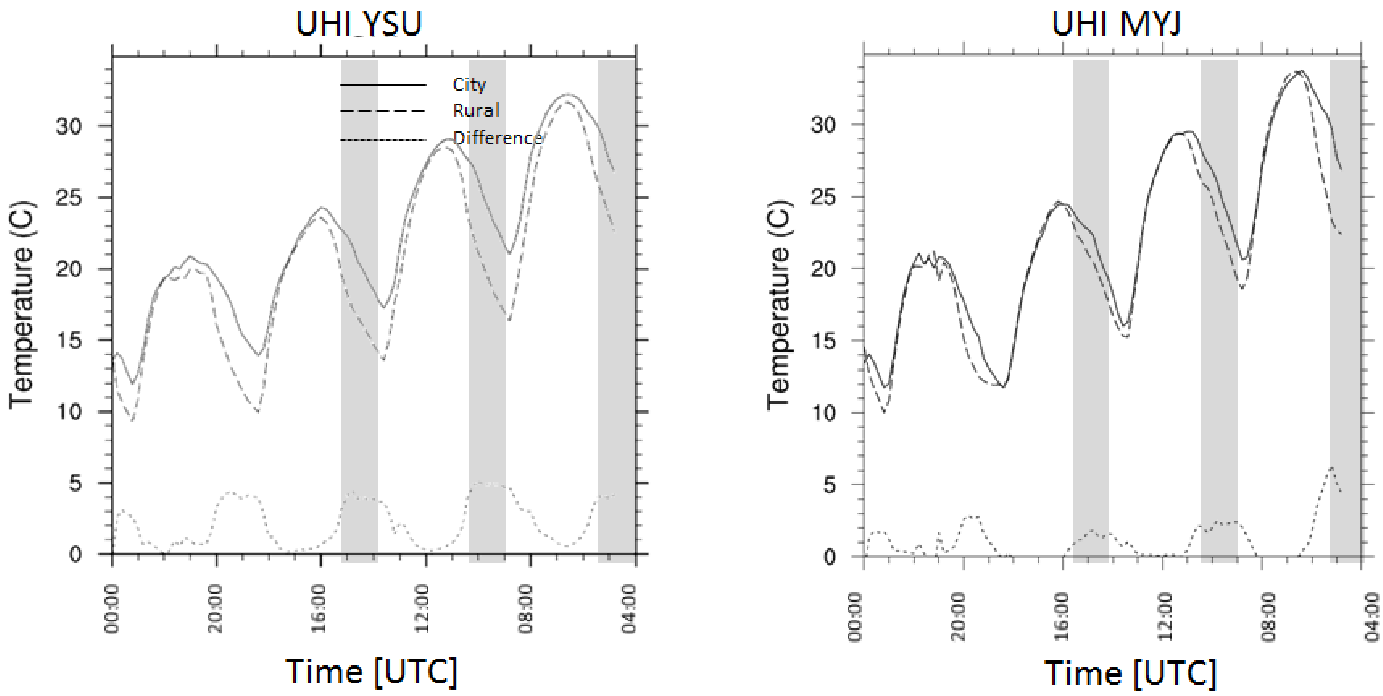


Figure 3: Diurnal variation of temperature in centigrade. The solid line stands for temperature in the city, dashed line for rural temperatures and dotted for the difference between these two. Grey panels depict night hours.

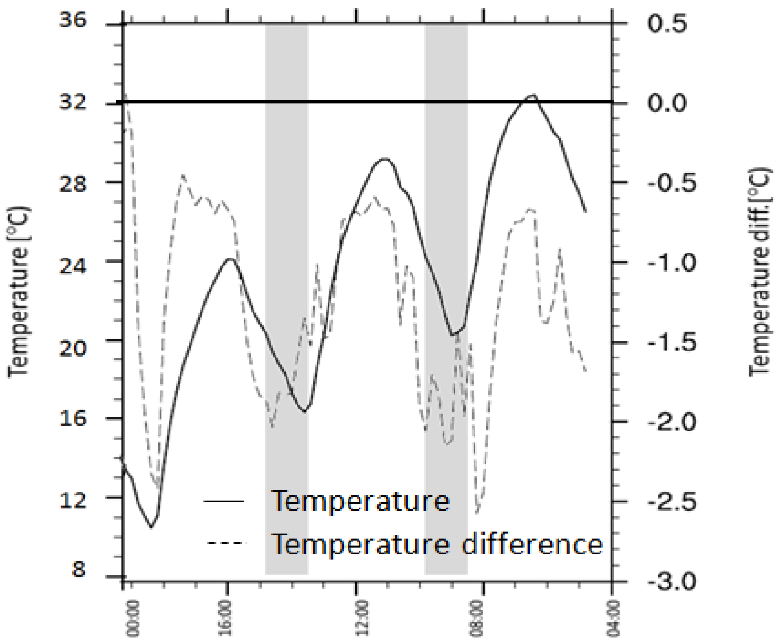


Figure 4: Diurnal variation of temperature and temperature change between YSU_G_SM27_1P and YSU_C. Chosen point is close to the park. Grey panels depict night hours.

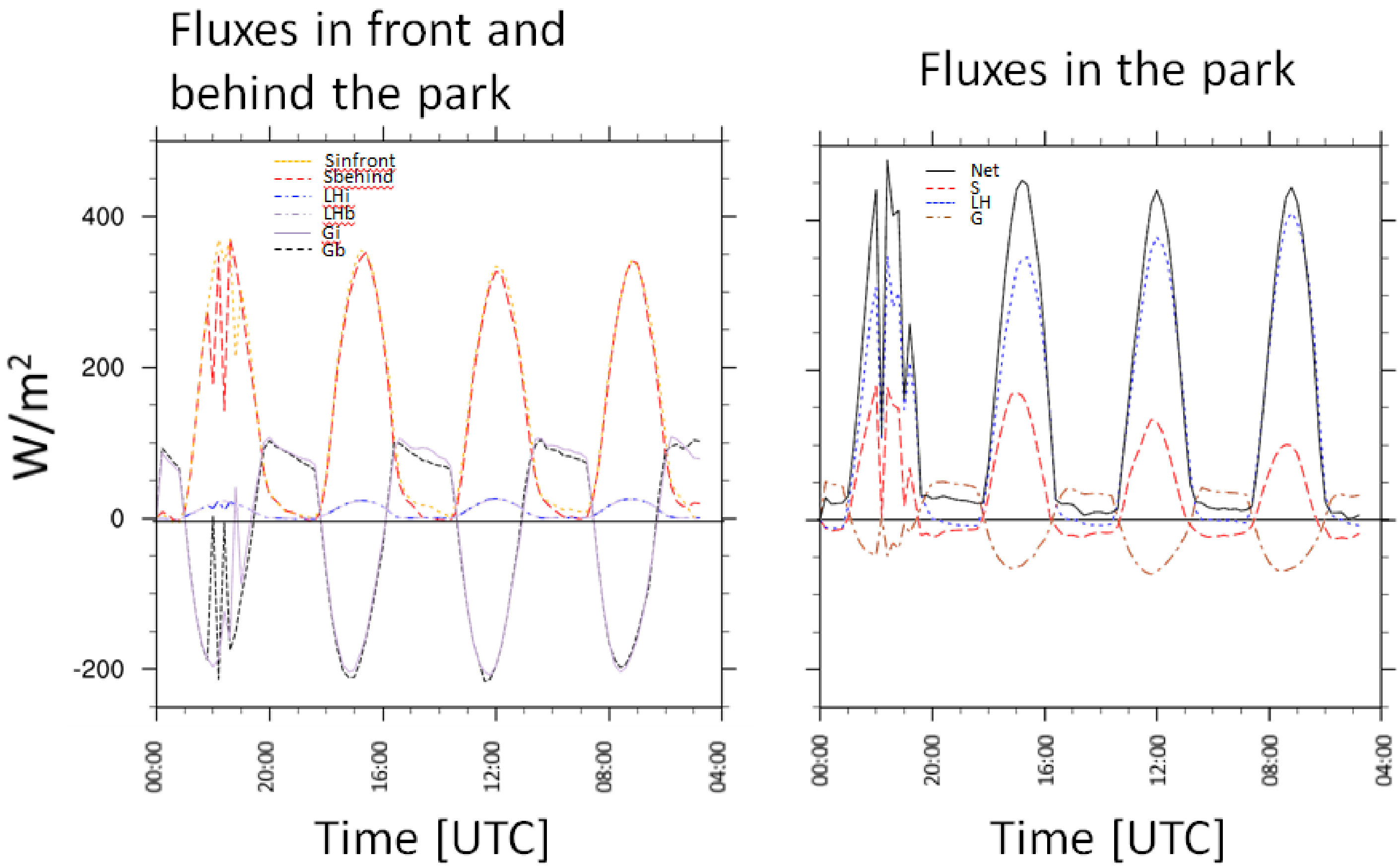
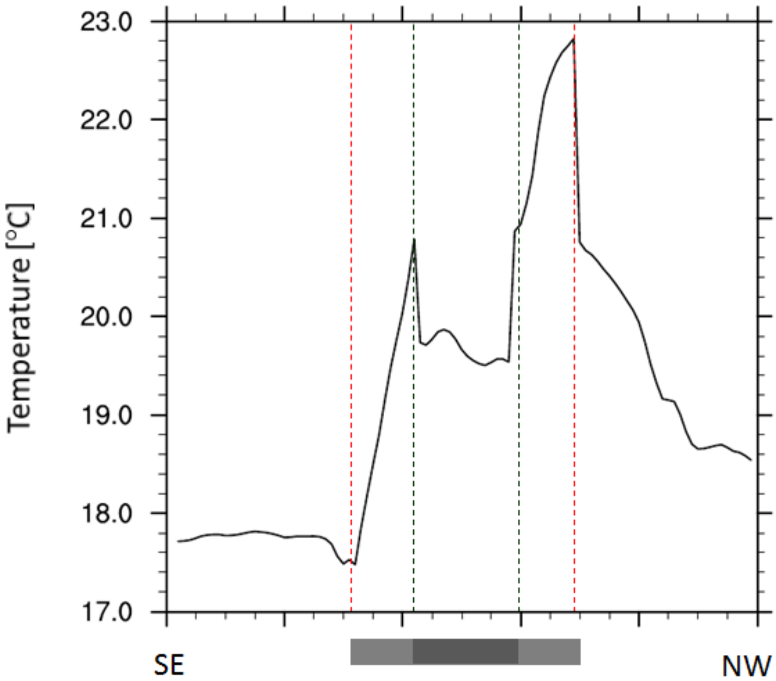


Figure 5: Energy balance components for different places in the city with respect to the park. LH stand for Latent heat flux, S for Sensible heat flux, G for ground flux and Net for Net radiation. B and i in the left panel a stand for behind and after respectively.



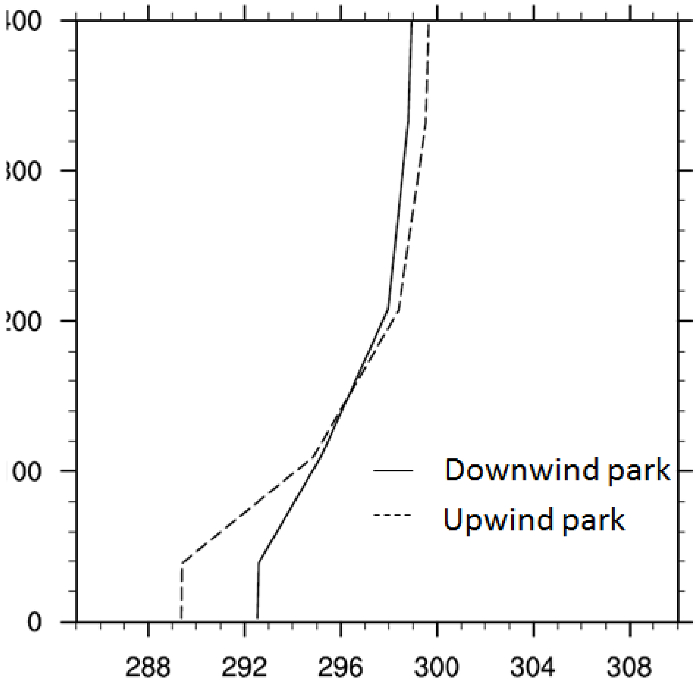


Figure 6a (left): Crosssection of temperature at 04:00 UTC 09-07-2010. The dashed red lines depict the urban borders and the dashed green lines the borders of the urban central park.

Figure 6b (right): Vertical profile potential temperature urban spot downwind and upwind of the city at 04:00 UTC 09-07-2010.

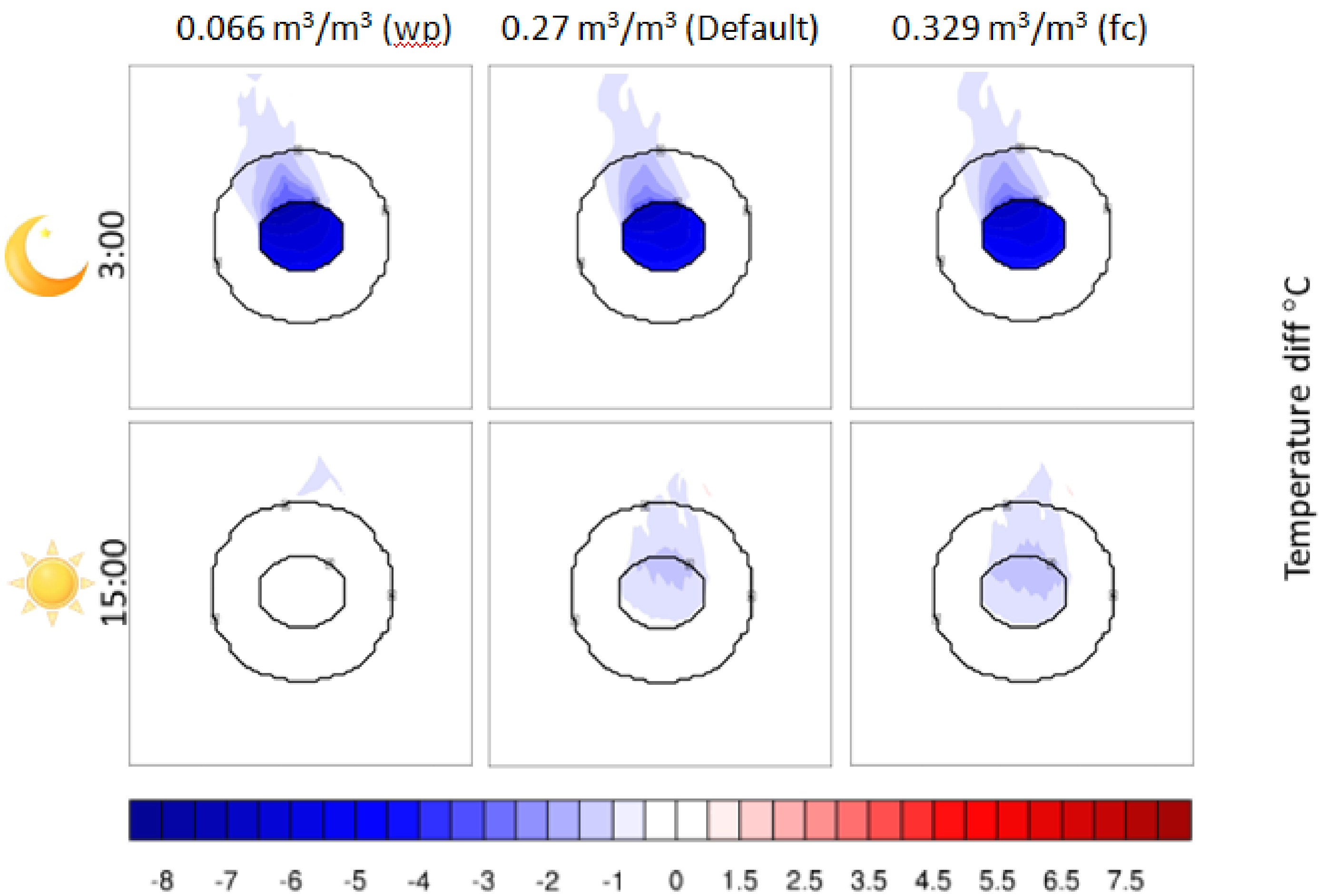


Figure 7: Influence of different soil moisture contents curing different times. Figure depicts difference between runs YSU_G_SM6.6_1P (left column), YSU_G_SM27_1P (middle column), YSU_G_SM32.9_1P (right column) and YSU_C. Temperature contours show every 0.5 degree change.

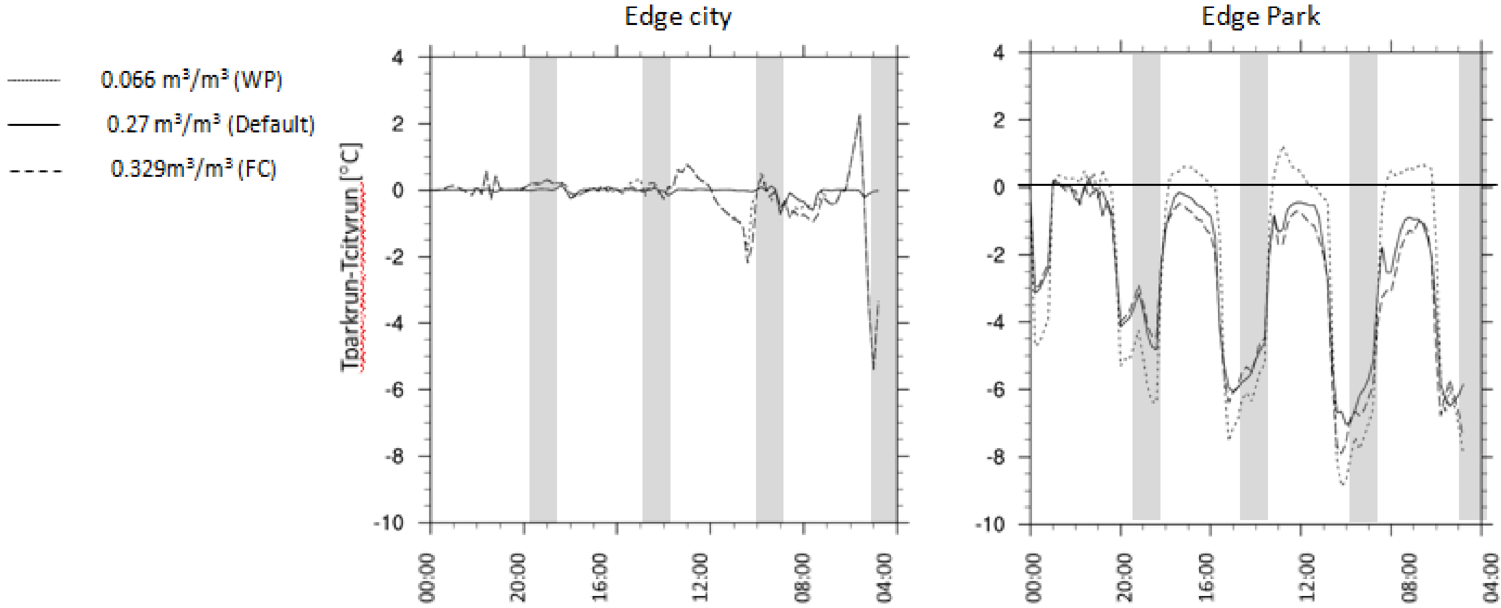


Figure 8: Influence of the parks of different soil moisture contents on its close downwind surroundings (right) and furthur in the city (left). Figures depict difference between YSU_G_SM6.6_1P (WP), YSU_G_SM27_1P (Default), YSU_G_SM32.9_1P (FC) and YSU_C.

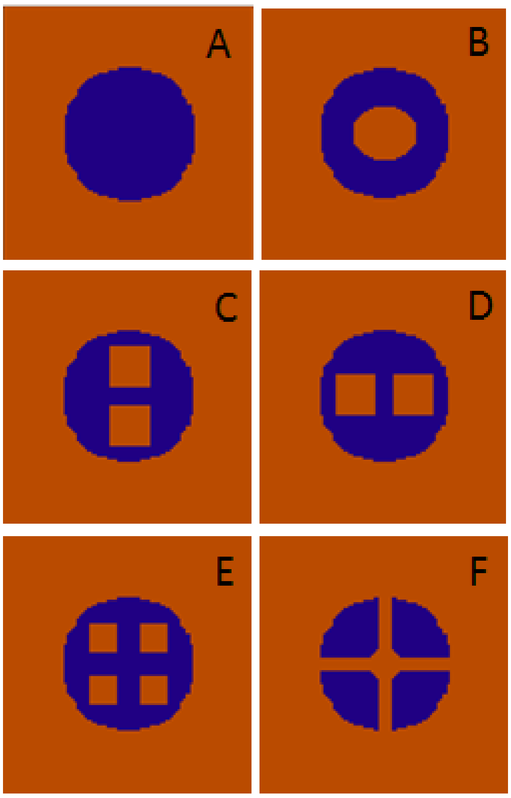


Figure 9: Cases of different distribution of vegetation over the city

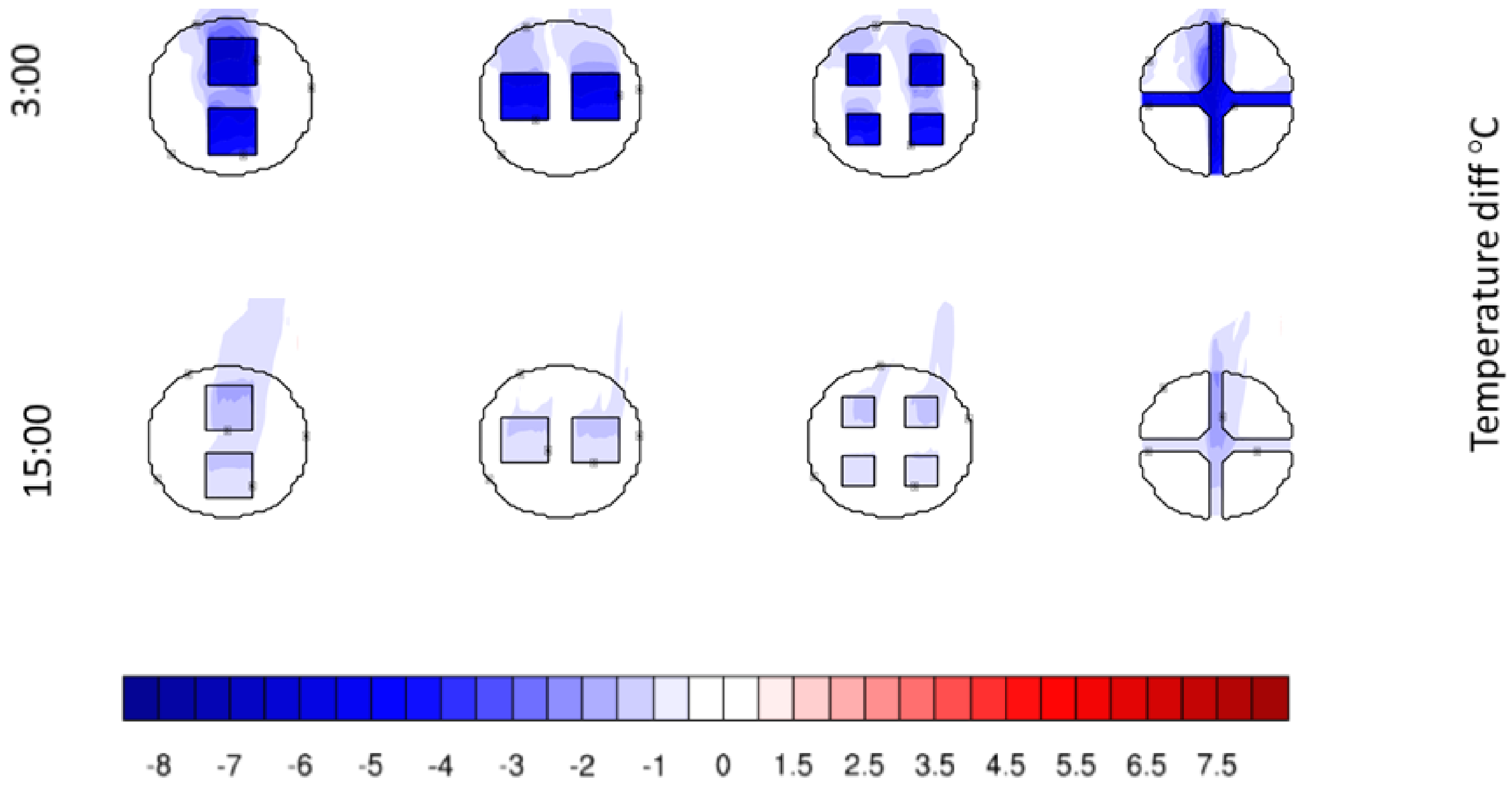


Figure 10: Influence of urban distribution temperature during day and night. Figure depicts difference between runs YSU_G_SM27_2PV (left column), YSU_G_SM27_2PH (second left column), YSU_G_SM27_4P (second right column), YSU_G_SM27_COR (right column) and YSU_C. Temperature contours show every 0.5 degree change.

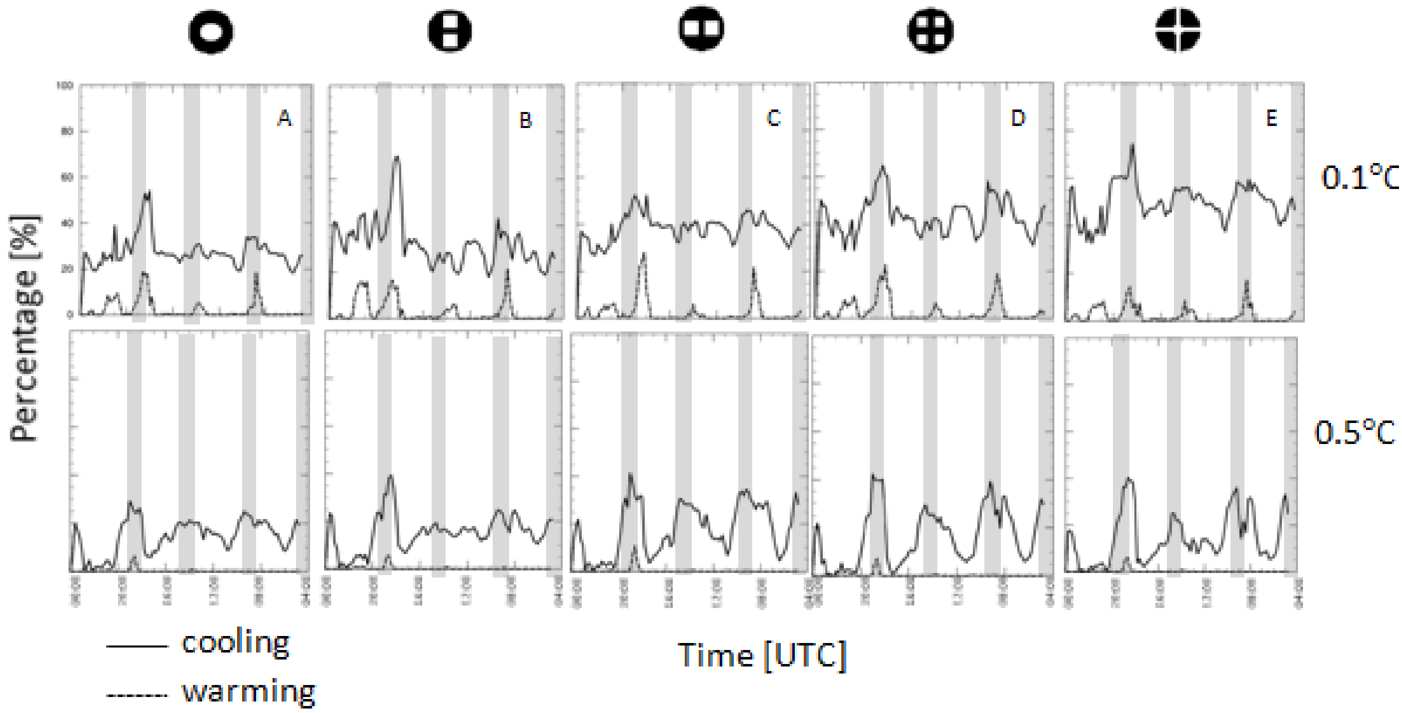


Figure 11: Percentage of the city influenced by the presence of the urban vegetation. Solid lines depict cooling effect and dashed lines warming effect. Top line shows percentage of the city influenced more than 0.1 °C (size of the plume) and bottom line percentage of the city influenced more than 0.5 °C. Each graph represents one of the model runs for different vegetation distribution (from left to right YSU_G_SM27_1P, YSU_G_SM27_2P (north-south), YSU_G_SM27_2P (west-east), YSU_G_SM27_4P, YSU_G_SM27_COR, YSU_G_SM27_INT).

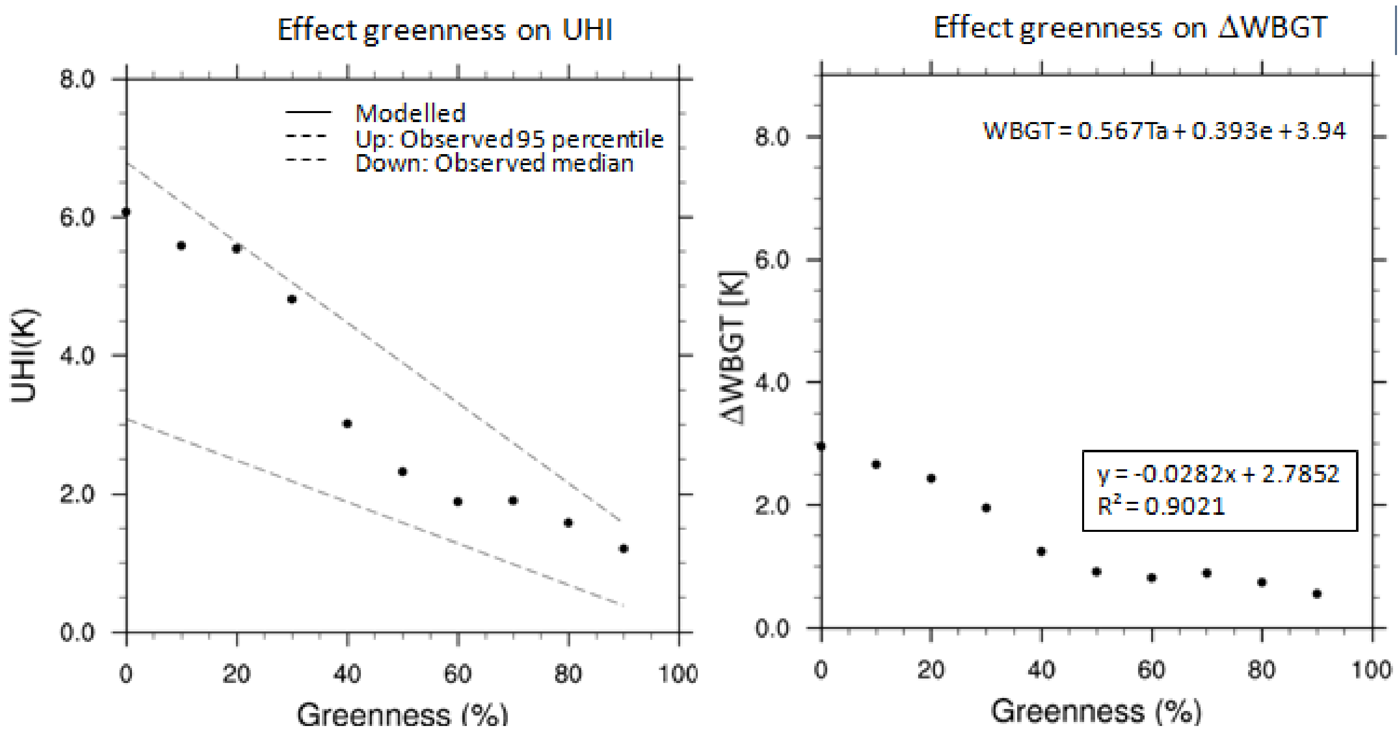


Figure 12: The effect of greenness percentage on the UHI. Figure depicts effect of greenness on the Temperature UHI (left) and the WBGT UHI (right). In the left figure dashed lines of an observational study of Steeneveld et al. (2011) are depicted.

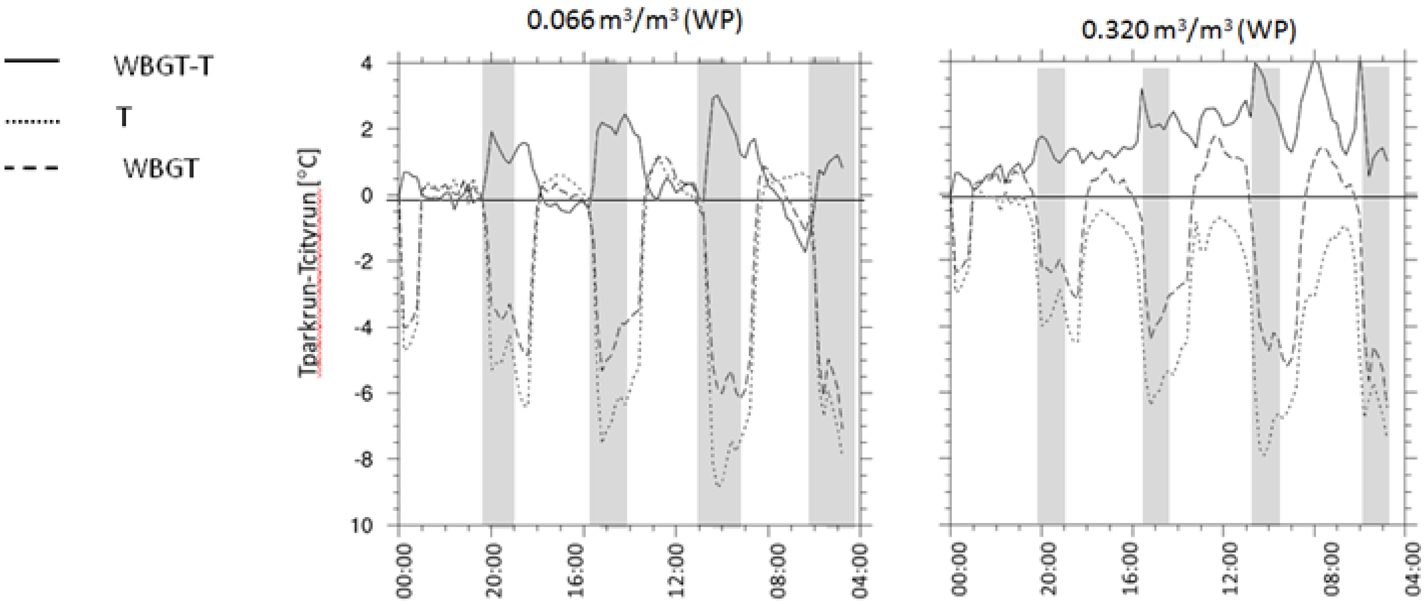


Figure 13: Comparison of the 2m temperature change and the WBGT change close to the park. Figure depicts difference between YSU_G_SM32.9_1P, YSU_G_SM32.9_1P and the run without park. Grey panels depict night hours.

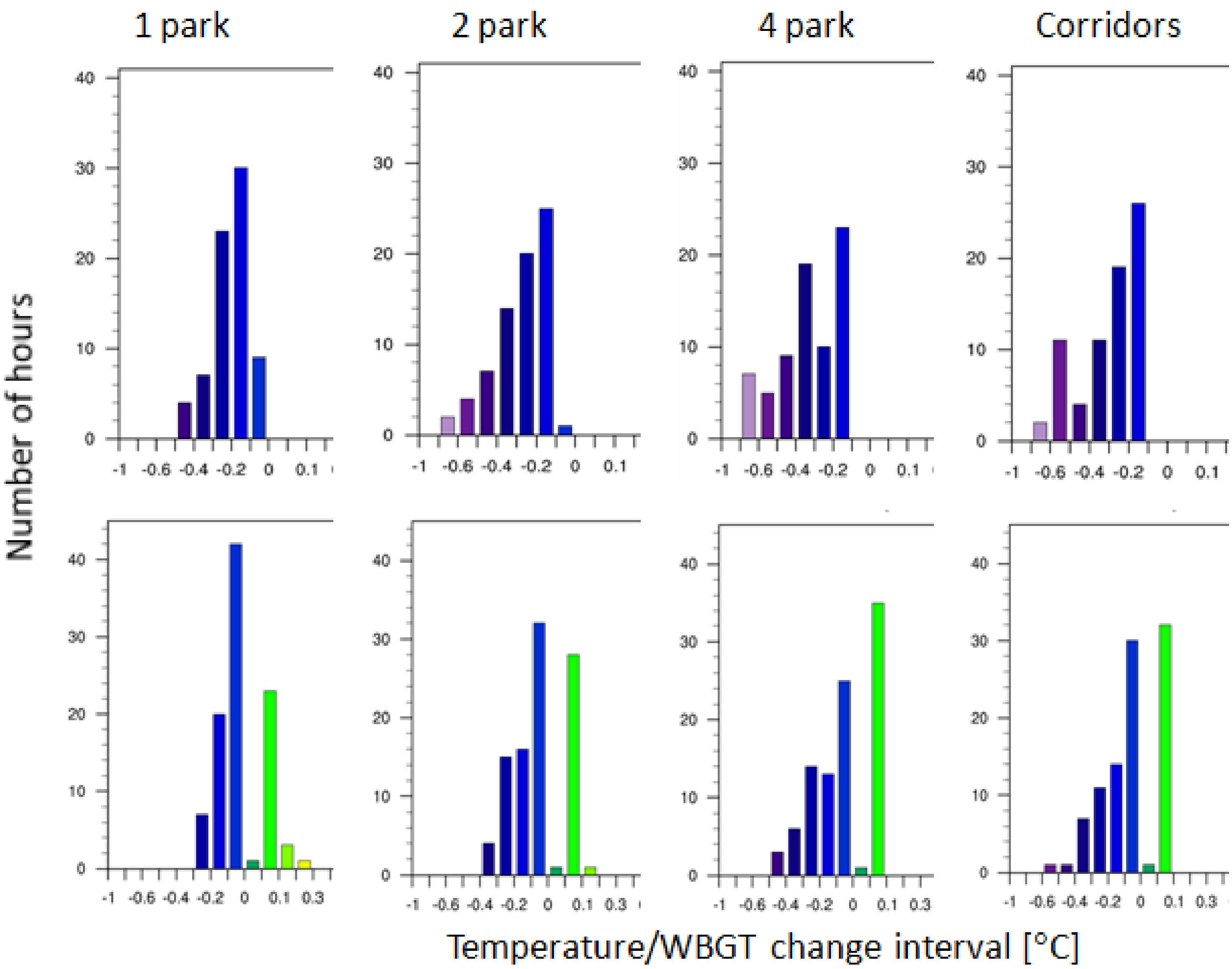


Figure 14: Frequencies of temperature change (top line) and WBGT change (bottom line). The bars depict the average temperature and WBGT change over the city per time step for YSU_G_SM27_1P, YSU_G_SM27_2PV, YSU_G_SM27_4P, YSU_G_SM27_COR.