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Master's Thesis

The cooling potential of allotment gardens during summer – case study „Kleingartenkolonie Johannisberg“ in Berlin

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Vorwort

Kleingärten sind mehr als Orte für den Selbstanbau von Obst und Gemüse, zum Entspannen oder geselligem Miteinander. Sie sind auch eine spezielle Form der Landnutzung, die sich, in Deutschland dem Bundeskleingartengesetz unterliegend, fest in das Stadtbild vieler deutscher Großstädte integriert hat. Kleingärten haben dabei auch ein wichtiges Potenzial in der Regulierung des Stadtklimas und sollten aufgrund ihres hohen Grünflächenanteils der bekannten städtischen Wärmeinsel zumindest in ihrer unmittelbaren Umgebung entgegenwirken. Durch Feldmessungen und deren Auswertung sollte diese Masterarbeit die Wichtigkeit von Kleingärten für Stadtklima von Großstädten wie Berlin hervorheben. Die geringe Anzahl von Studien in diesem Bereich unterstreicht die Notwendigkeit einer solchen Untersuchung. Ebenso wichtig ist das Verstehen der mikroklimatischen Relevanz von Kleingartenanlagen vor dem Hintergrund ihres kontinuierlichen Rückganges in Städten wie Berlin, vor allem zu Gunsten der Schaffung neuen Wohnraums.

Ich sehe in dieser Arbeit einen wichtigen Beitrag die Stadtplanung in Zukunft nachhaltiger ausrichten und zugleich das Innenstadtklima maßgeblich verbessern zu können. Der mikroklimatische Einfluss von Kleingärten und ihr Potenzial für ein umwelt- und menschenfreundlicheres Stadtbild- und Stadtklima sollten keineswegs unterschätzt werden.

Ich bedanke mich ganz herzlich bei allen, die mich in meiner Arbeit unterstützt haben.

An erster Stelle möchte ich mich vor allem bei Herrn Professor Dieter Scherer, Vorsitzender des Fachgebiets Klimatologie der Technischen Universität Berlin, bedanken, der mich nach der Vorstellung meines Exposés zu der Durchführung meines Themas ermutigt hat und sich persönlich als Supervisor für diese Arbeit anbot. Mein spezieller Dank gilt auch Herrn Dr. Fred Meier, der mir die nötigen Messgeräte zur Verfügung stellte und wichtige zusätzliche Tipps zum Aufbau der Arbeit gab. Daniel Fenner möchte ich hier für die Aufbereitung der zusätzlichen meteorologischen Daten des Messnetzes der Technischen Universität danken. Mein spezieller Dank gilt auch Herrn Dipl. Ing. Hartmut Küster, der mir das HuMVe zu der Kolonie brachte und mir half es für meine Messungen aufzubauen.

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Ein weiterer ausdrücklicher Dank von mir geht an Frau Anja Ewers vom Straßen- und Grünflächenamt Charlottenburg-Wilmersdorf, die mir das Anbringen meiner Messgeräte an den Straßenbäumen entlang der Homburger Straße genehmigte.

Meinen Dank möchte ich auch an meinen Mann Marius richten, der mir immer zur Seite stand und mir wertvolle Tipps gab, das Korrekturlesen meiner Arbeit und auch das Ziehen des Human Meteorological Vehicles während der mobilen Messungen übernahm. Bei meinem Sohn Richard bedanke ich mich sehr für seine Geduld, dass er mich oft bei meinen Besuchen zu der Kolonie begleitete und Verständnis hatte, wenn ich nicht viel Zeit für Ihn hatte. Ich möchte mich auch ganz herzlich bei meiner lieben Mama bedanken, die immer da war, wenn Not am Mann war.

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ACI	Allotment Cool Island
ACII	Allotment Cool Island intensity
BKleingG	Bundeskleingartengesetz
BDG	Bundesverband Deutscher Gartenfreunde
DWD	Deutscher Wetterdienst
PCI	Park Cool Island
PCII	Park Cool Island intensity
TU	Technische Universität
UES	Urban Ecosystem Services
UHI	Urban Heat Island
UHII	Urban Heat Island intensity

Declaration of originality

Hereby I declare that I wrote this thesis myself with the help of no more than the mentioned literature and auxiliary means.

Agnieszka Anna Schlegelmilch

Abstract

Due to global warming and the proceeding urbanisation in big parts of the world approaches to mitigate the problematic effects of the urban heat island (UHI) are more important than ever before. A well-known sustainable solution to mitigate the urban overheating are urban parks. However, the potential of allotment gardens as integral part of German, but also other European cities to reduce the air temperature was so far nearly not considered. Although research during the last decades showed that allotment gardens provide many important Urban Ecosystem Services (UES), studies of the UES of allotment gardens are comparatively rare. All the more exists a lack of actual studies investigating the cooling effect of this specific kind of urban land use. The work shall close this gap. Therefore, a measurement campaign from Mai 31, 2017 to July 2, 2017 was carried out in the location of the allotment garden colony Johannisberg in Berlin. For the findings nine fixed HumiLog „rugged“ sensors were used which measured continuously at a height of 2.5 m. The study was supplemented by mobile measurements which also measured the wind speed in a height of 3 m. The work comes to the conclusion that the colony Johannisberg produced a specific “Allotment Cool Island” (ACI) in the inner-city area of Berlin. Colony Johannisberg proved to be up to 3.2 K colder than its urban neighbourhood, whereby in radiation nights it decreases the air temperature of its urban neighbourhood typically by 1–2 K. The measured extend of the cooling effect during radiation nights was 80–160 m from the colony borders in the urban neighbourhood. The extension of the ACI is caused by an own microscale wind system of the allotment garden colony, the “allotment breeze”, which was firstly measured at all in this work. Both, the ACI and the extension of the cooling effect proved to be most pronounced in situations with a strong UHI and therewith when they are most needed. The “ACI” and the “allotment breeze” are two new terms, introduced with this work to distinguish the positive microclimatic effects of urban allotment gardens as a specific kind of green private land use of urban free space from those of other public green spaces in the city.

Zusammenfassung

Aufgrund der globalen Erwärmung und der fortschreitenden Urbanisierung in weiten Teilen der Welt sind Maßnahmen zur Verbesserung des Stadtklimas und zur Minderung der negativen Auswirkungen der städtischen Wärmeinsel (UHI) wichtiger denn je. Eine bekannte nachhaltige Lösung zur Verringerung der innerstädtischen Überwärmung sind Parkanlagen. Das Potenzial von Kleingärten als fester Bestandteil deutscher, aber auch anderer europäischer Städte zur Senkung der Lufttemperatur wurde bisher dagegen kaum berücksichtigt. Die Forschung in den letzten Jahrzehnten hat gezeigt, dass Kleingärten viele wichtige städtische Ökosystemdienstleistungen (UES) bereitstellen. Bisher existieren aber verhältnismäßig wenig Studien über die UES von Kleingärten. Noch größer ist der Mangel an aktuellen Studien, die den Kühleffekt dieser spezifischen Art der städtischen Landnutzung untersuchen. Die vorliegende Arbeit soll diese Lücke schließen. Daher wurde eine Messkampagne vom 31. Mai 2017 bis 2. Juli 2017 am Standort der Kleingartenkolonie Johannisberg in Berlin durchgeführt. Für die Messung wurden neun feste HumiLog "rugged" Sensoren verwendet, die kontinuierlich in einer Höhe von 2,5 m gemessen haben. Die Studie wurde durch mobile Messungen ergänzt, bei denen auch die Windgeschwindigkeit und Windrichtung in 3 m Höhe gemessen wurden. Die Arbeit kommt zu dem Ergebnis, dass die untersuchte Kolonie Johannisberg im innerstädtischen Bereich von Berlin ein spezifisches "Allotment Cool Island" (ACI) bildet. Die Kolonie Johannisberg erwies sich als um bis zu 3,2 K kälter als die städtische Umgebung, wobei sie die Lufttemperatur ihrer städtischen Umgebung in Strahlungsnächten typischerweise um 1–2 K senkt. Der gemessene Kühleffekt während der Strahlungsnächte reichte 80–160 m von den Koloniegrenzen in die angrenzende Wohngegend. Die räumliche Ausdehnung des ACI in Gebiete außerhalb der Kolonie wird durch ein eigenes, mikroskaliges Windsystem ermöglicht, der sogenannten "allotment breeze", die in dieser Arbeit zum ersten Mal überhaupt gemessen wurde. Das ACI und die Ausdehnung des Kühleffekts der Kleingartenkolonie waren in Situationen mit einem starken UHI am stärksten ausgeprägt und damit genau dann, wenn sie am meisten benötigt werden, um das UHI zu reduzieren. Beide Begriffe, das "ACI" und die "allotment breeze" werden mit dieser Arbeit neu eingeführt, mit dem Ziel den positiven mikroklimatischen Effekt von Kleingärten als privat genutzte urbane Grünflächen von dem öffentlicher Grünflächen in der Stadt in Zukunft unterscheiden zu können.

1 Introduction

Climate optimised urban planning was never as important as today. The increased need to find sustainable solutions to improve the climatic conditions in urban areas has mainly two reasons: Urbanisation, which is especially a challenge in developing and emerging countries (BMZ, 2014) and the proceeding global warming (IPCC, 2014). For Europe the topic becomes even more relevant since heat waves should become more frequent and longer lasting in future (Meehl and Tebaldi, 2004, Kántor et al., 2016). Cities are most affected by these changes since they generally have a higher mean air temperature then their rural surroundings, caused by the physical properties of their surface. The resulting, meanwhile well-known urban heat island (UHI) phenomenon, occurs in mid-latitudes mostly during the night and can lead to remarkable temperature differences between the urban and rural area. During summer the UHI intensity in London can reach values about 9 K (Doick et al., 2014), an even higher urban overheating was determined for Berlin with 11 K (Fenner et al., 2014) and for Moskau with 14 K (Lokoschenke, 2014). Such increases in air temperature show clearly why heat stress is the most important stress factors in the urban environment (Gulyás et al., 2006). The superposition of the UHI with the rising global temperature (Emmanuel and Krüger, 2012) and the further growth of cities make the topic to a real challenge in future. More relevant than the negative impact on thermal comfort are the consequences of the UHI on human health. In France the heatwave of 2003 caused 15.000 additional deaths (Fouillet et al., 2006). For Berlin as capital city of Germany it could be proved that 5 % of the cases of death in Berlin within the period from 2001 to 2010 could be statistically attributed to higher air temperatures (Scherer et al., 2013). Consequently, the UHI can lead to raised rates of mortality – especially in connection with heat waves (Heaviside, 2016).

At least as important as the investigation of the UHI and its consequences is the research of measures which are appropriate in order to mitigate the UHI effect. One common and sustainable possibility to reduce heat stress in cities are urban parks, which are frequently colder than their urban surrounding (Bowler et al., 2010). This phenomenon which is known as the park cool island (PCI) has mostly a dimension of 1–3 K but can also reach significantly higher values (Spronken-Smith and Oke, 1998). Furthermore, park areas can also have a cooling effect on their environment, which occurs especially. In mid-latitudes, the temperature-regulating behavior of such green spaces at night is especially important, because then also the UHI is mostly distinctive.

Since increased minimal temperatures during heat waves can increase the mortality rate (Dousset et al., 2011) and already a reduction of air temperature of about a few degrees Celsius at night can be very important for risk groups like older people (Clarke and Bach, 1971; Höppe, 1991), green areas can significant impact the quality of life in a city.

Another kind of urban green space that can positively influence the urban climate are allotment gardens. Despite their widespread use in urban areas, the common benefits of allotment gardens are little investigated in comparison with other green areas (Haase et al., 2014). Even lower is the level of knowledge about the climatic influence of allotment gardens on their urban environment. Here exists a big gap of knowledge, since only a few works analysed this topic, whereby these studies are usually more than 30 years old.

This work should close this gap and clarify in what extend allotment gardens can improve the urban climate by reducing the air temperature. The work should thereby quantify the influence of allotments on the example of one allotment garden area in Berlin and discuss their relevance as integral part of the city structure.

2 Motivation, hypothesis and intentions

The motivation of this work was it to investigate a particular kind of green space within a big city which has the potential to reduce urban heat stress caused by the UHI, but which had only attracted little attention so far in the research of urban climatology. An additional incentive to choose this topic was that I myself also own a small allotment garden in the urban fringe area of Berlin, where I felt the supposed climatic differences on my own.

Allotment gardens, as a special kind of land use, are in urban areas of Germany, but also in neighbouring countries such as Poland and England a widespread and a correspondingly important part of the urban structure and the urban ecosystem (Speak et al., 2015; Bundesverband Deutscher Gartenfreunde e.V., 2017).

In Germany, allotment gardens are subjected to uniform rules, summarised in the "Bundeskleingartengesetz" (BKleingG). For example, BKleingG§ 3 determines a maximum area for the allotment garden of 400 m², while the arbour only can have a size of 24 m² (Bork, 2008). Due to the small portion of the arbour to the total area of the allotment garden, allotment gardens should be in general mostly green and unsealed.

This general assumption should be also applicable for whole allotment garden colonies where paths, arbours and other artificial surfaces only take up a small part of the total area. The consideration of allotments as a low sealed, park-like but distinct specific private land use class of a city should apply generally, unless of colony- and nationwide deviations in size and construction of the allotments gardens.

From this approach, the following hypothesis were created:

1. “Allotment gardens as a specific kind of private usage of urban free space have a cooling effect comparable to urban parks. Because of their special land use the should be distinguished from other public green urban areas like parks. Accordingly, the temperature depression resulting by allotment gardens should be quantified with an own index, the “allotment cool island” (ACI).”

2. “Allotment gardens can cool their urban surroundings during radiation nights by an own microscale wind system, the “allotment breeze”, which transports cold air from the colony in its surrounding urban area.”

The following literature review showed that so far only very few studies investigated the thermal cooling effect of allotment gardens. However, the few existing results support the assumption of a cooling effect of allotment gardens on their immediate environment only partially. Accordingly, this work should provide a meaningful contribution in this direction and clarify to what extent allotment gardens have a cooling influence on their environment. Another very important point that led to the implementation of this work is the steady decline of allotment gardens in big cities like Berlin, mostly due to the construction of new residential areas. The therewith associated demolition of allotment gardens stays in hard contrast to the reputation of Berlin, which is so far the metropolis with the most allotment gardens in Germany.

Until now, numerous Ecosystem Services have been verified for allotment gardens (Breuste and Artmann, 2015; Speak et al., 2015). However, studies which investigated the influence of allotment gardens on the microclimate in the city are very rare.

With the air temperature this work should investigate a quantifiable parameter, which clearly shows the climatic influence of allotment gardens on their urban neighbourhood and which should be an appropriate indicator on which allotment gardens can refer in future. Against the background of the declining number of allotments, the low level of research concerning the microclimatic influence of allotments in the city, the often pronounced UHI in Berlin and the expected increase in heat stress in the future, this work has the following intentions:

1. Quantify the thermal influence of an allotment garden colony in Berlin on its urban environment.
2. Compare the results of the allotment garden colony with regard to the temperature with results of other green urban areas.
3. Evaluate the value of allotment gardens for the regulation of the urban microclimate.

3 Allotment gardens and urban climate

The following part gives an overview over the historical development and the actual status of allotment gardens with focus on Berlin. Afterwards, the Urban Ecosystem Services of allotment gardens will be presented. Finally, the causes of the urban climate will be explained and connected with findings of the cooling effect of urban parks.

3.1 Development of allotment gardens in Berlin

In 1819, the English government passed a law that governs the leasing of land to the unemployed and local poor, which was the begin of the development of allotment gardens. With the same objective the so called “Armengärten” were introduced 1830 in in Kiel in Germany. In 1833 the first “Armengärten” were established in Berlin, were they were used invariably for potato cultivation (Landesverband Berlin der Gartenfreunde e.V., 2007). This type of land use, which was subjected to strict rules, reached its culmination in 1882, when it supported 2876 families. Fourteen years later, the “Armengärten” became closed again (Farny and Kleinlosen, 1986). The final step for the development in the direction of today's allotment gardens was the possibility to lease areas of nearly 300 m² on the "Schlächterwiesen" in Berlin Kreuzberg since 1862 to grow diverse kinds of vegetables (Farny and Kleinlosen, 1986). The number of such leased residual property areas in Berlin increased afterwards rapidly: In 1880 existed already 2,500 of tenants known as "Pflanzer", in 1895 they were already 40,000 (Senatsverwaltung für Stadtentwicklung und Umwelt, 2012). This significant increase happened parallel to the extreme urbanisation that took place in Berlin during the 19th century. The population increased from 1880 to 1900 from 750,000 to 1,900,000 (Farny and Kleinlosen, 1986). Already at that time, the primary function of allotment gardens was not the self-supply with food, but the possibility to escape from the cramped housing conditions. In 1911 100,000 overcrowded apartments existed with more than 4 people in one heated room (Farny and Kleinlosen, 1986) whereby already around 1900 48 % of all apartments in Berlin were backyard apartments. The need for some freedom for the mostly from the country originating population was accordingly strong.

However, the tenants at that time were strongly exposed to the arbitrariness of landholders, who managed the open spaces of the city as a temporary source of income before their planned development (Landesverband Berlin der Gartenfreunde e.V., 2007). Low rights, high lease costs and forced schank charges were thus closely connected with the leased terrain. As a measure the tenants organized themselves as associations to lease their own land. Eight of these associations merged in 1901 to form the „Vereinigung sämtlicher Pflanzvereine Berlins und Umgegend“ from which the "Verband der Laubenkolonisten Berlin und Umgebung" emerged in 1911.

Another development in this direction were the workers' gardens of the society “Rotes Kreuz”, of which the first was created in 1901 in Berlin Charlottenburg (Landesverband Berlin der Gartenfreunde e.V., 2007). In 1906 the workers' gardens closed together to the "Verband deutscher Arbeitergärten". From this and 17 further associations the "Zentralverband deutscher Arbeiter- und Schrebergärten" was founded (Landesverband Berlin der Gartenfreunde e.V., 2007). After the allotments of Berlin in World War I also served as a food source for the urban population (Senatsverwaltung für Stadtentwicklung und Umwelt, 2012), joined the social-democratic-characterised and meanwhile named "Verband der Laubenkolonisten Berlins und Umgebung" and the charitable characterised “Zentralverband deutscher Arbeiter- und Schrebergärten“ together in 1921 (Farny and Kleinlosen, 1986). Driven by the post-war consequences and the inflation, the extension of allotments in Berlin reached its present culmination in 1925 with a total area of 5793 ha (Farny and Kleinlosen, 1986). Subsequently, the total area of allotment gardens in Berlin decreased again, but remained high up to the Secound World War with a total area of over 4400 ha. The importance of allotments in Berlin rose clearly again due to supplying problems and housing shortage after the Second World War until the early 1950s, when they were also used as residence (Senatsverwaltung für Stadtentwicklung und Umwelt, 2012).

With the following economic recovery, the number of allotment gardens in Berlin decreased again clearly (Farny and Kleinlosen, 1986). On the areas of the former allotments new housing estates were built or they were instead replaced by public facilities, industry, business houses or roads (Mahler, 1972). In 1976 the Berlin organisation of allotment gardeners "Landesverband Berlin der Gartenfreunde e. V." joined to the nationwide "Bundesverband Deutscher Gartenfreunde e. V.". The collective basis for the allotments in this considerable association is since 1983 the Germany-wide consistent Bundeskleingartengesetz (BKleinG).

3.2 Actual status of allotment gardens in Germany and Berlin

Most allotments in Germany are subordinated to the “Bundesverband Deutscher Gartenfreunde e. V. (BDG)“. This association includes 14,000 clubs, which are subject to 515 associations, which in turn belong to 20 state associations (BDG, 2017). Allotment gardens of the BDG have a mean extend of 370 m², without subtracting community areas like paths, the club house and the fairground the mean area is 438 m² (BDG, 2017). Including tenants, their families and friends nearly five million people make use of allotment gardens in Germany (BMVBS, 2013; BDG, 2017). Currently the allotment gardens of the BDG covers an area of 460 km² (46,000 ha). However, the number of allotments in Germany decreased within the last years clearly: In 2006 1,012.000 allotment holders existed who were subordinated to the BDG (Bundesministerium für Verkehr, Bau und Stadtentwicklung and Bundesamt für Bauwesen und Raumordnung, 2008). Until 2017, their number dropped to 934,000 (BDG, 2017), which is a decline of 78,000 allotments representing a relative decrease of 7.7% in 12 years.

Berlin as the greenest metropole in Europe (Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2017 a) offers more allotment gardens than any other German city. Nevertheless, the number of allotments in Berlin is decreasing almost continuously. From 1996 to 2015, the total area of all allotment gardens in Berlin declined from 35.60 km² to 29.90 km² in the years 1996 to 2015 (Statistisches Landesamt Berlin (2004–2006), Amt für Statistik Berlin-Brandenburg (2005–2016)). Thus, the area of allotment garden in Berlin shrank by 16 % within 20 years. At the same time, the number of allotment holders declined from 83,274 to 73,030. Considering Berlin's city area of 891.69 km², the relative area of allotment gardens in the 20 years between 1996 and 2015 has fallen significantly from 3.99% to 3.35%. An overview of this development is shown in Fig. 1.

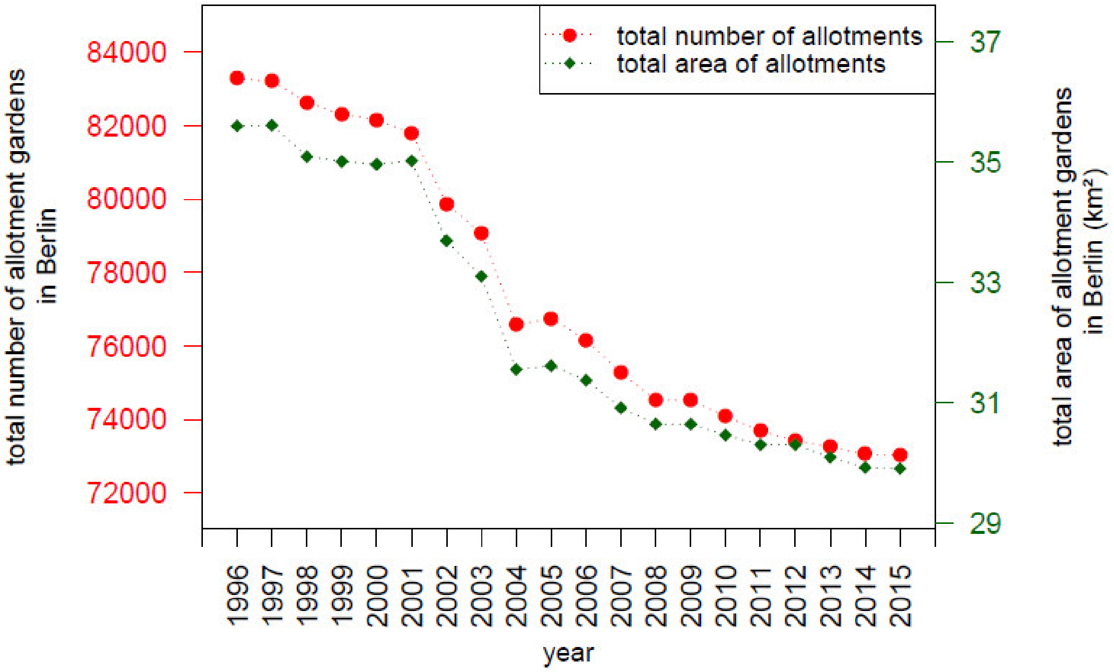


Fig. 1: Total number of allotment gardens and associated allotment area in Berlin from 1996 to 2015. Data sources: Die Kleinen Berlin-Statistiken (2004–2016): Statistisches Landesamt Berlin (2004–2006), Amt für Statistik Berlin-Brandenburg (2005–2016).

Despite the obvious decrease in number of allotment gardens, they amount with 25.8 % the second highest percentage of public green spaces in Berlin direct after green and recreation areas (Fig. 2), whereby all public green spaces together cover 13 % of the total area of Berlin. These numbers underline the relevance of this kind of green infrastructure for the city.

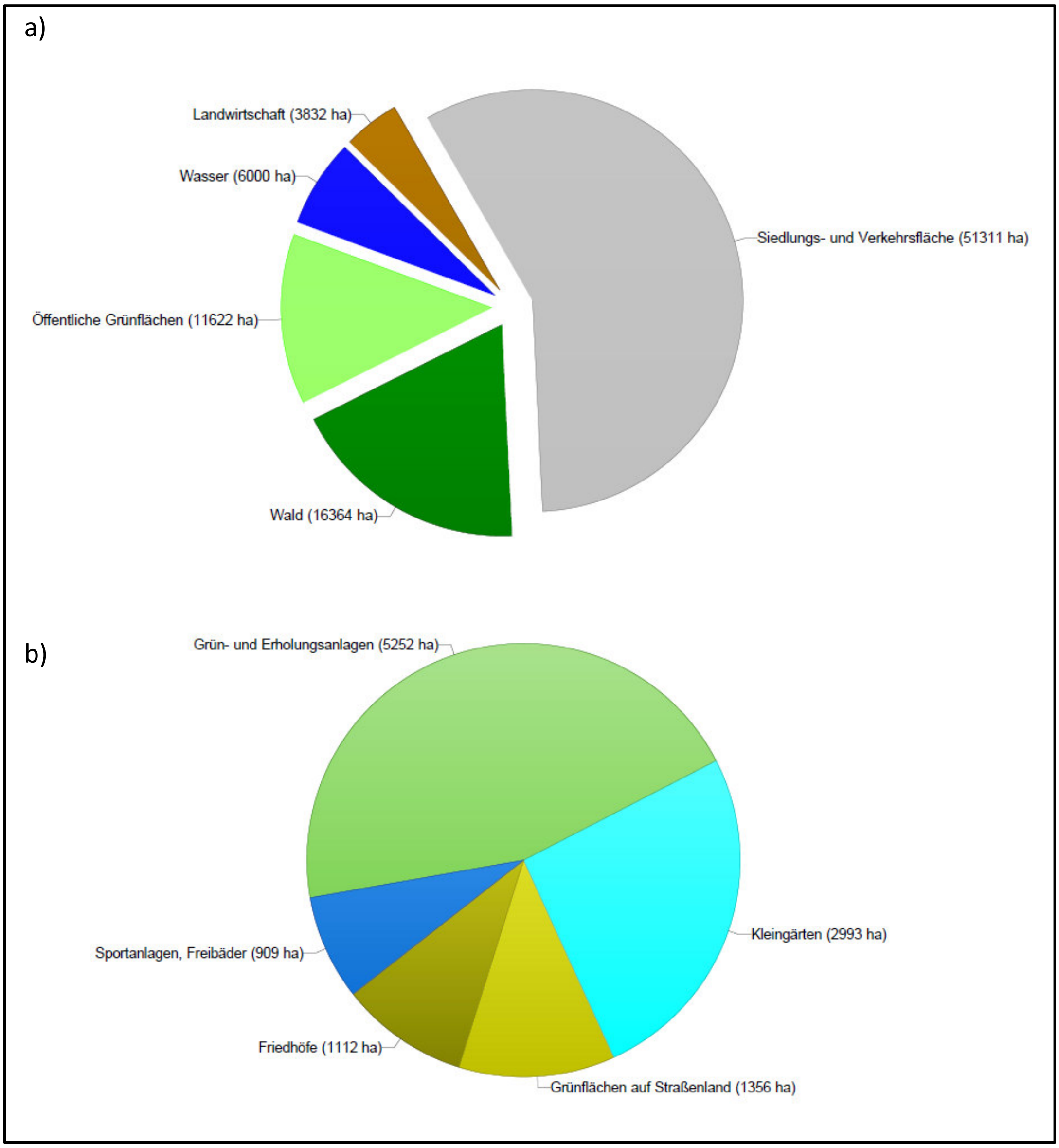


Fig. 2: Distribution of the amount of different urban landcover classes (a) and the subdivision of public green space into its different portions (b). Status: 31/12/2016. Data source: Senatsverwaltung für Umwelt, Verkehr und Klimaschutz (2017 b).

3.3 Allotment gardens and Urban Ecosystem Services

According to §1, passages 1–2 of the Bundeskleingartengesetzes (BKleingG), an allotment garden is a garden that conduces the allotment holder for non-commercial, horticultural use to produce horticultural products for the private use and for recreation, which is located in a complex of several allotment gardens with common facilities like play areas and club houses. Further guidelines should ensure the maintenance of land containing allotments. For example, at least 1/3 of the allotment garden has to be used “allotment-like” with fruit trees and vegetables whereby 10 % of the total alotment area have to be covered by bed plots (Bundesverband Deutscher Gartenfreunde, 2017). Despite of these rules, the relevance of self-sufficiency of allotment gardens decreases with a trend to leisure consumption (Breuste and Artmann, 2015). However, this trend is not new (Jansen, 1986; Farny and Kleinlosen, 1986).

Although the general shift in the function of allotments from a food supplying to a recreation area, allotment gardens suffered no loss, but a significant expansion of their functions (Jansen, 1986). For example, the importance of allotment gardens as an ecological resource for sustainable urban development was of great interest in the recent years, especially in the sections of soil conservation, maintenance of a balanced water balance, habitat for plants and as animals and climatic compensation area (BDG, 2002).

Such urban ecosystem services (UES), are essential to the quality of life in urban areas because humans and their ecosystems are inextricably linked (MEA, 2005). The importance of green spaces for the city is also evident in the fact that their availability plays an increasingly important role in the quality of life of the population of a city (Borysiak and Mizgajski, 2016). Allotment gardens play a key role in this context, since they can offer a greater capacity for Urban Ecosystem Services (UES) than urban parks in certain areas (Speak et al., 2015), also when they may differ from country to country in terms of their structure and area subdivision. Thus, allotment gardens are a very valuable component of urban space.

Furthermore, allotment gardens offer numerous UES that cover all four functional categories defined by the Millennium Ecosystem Assessment: Allotment gardens offer, in contrast to urban parks, many “provisioning services”, such as self-supply through harvesting and growing animal feed. A study from Salzburg, Austria concludes that the allotment gardeners cover 44% of their vegetable needs through their allotments according to surveys, whereby nowadays the freshness, quality and better taste in comparison to the otherwise available goods stay in the foreground (Breuste and Artmann, 2015). The arguments accord with the current trend towards healthy nutrition and bio-products.

Allotment gardens also supply important "supporting services", for example for the biodiversity by providing habitats for rare plants and animals (Endlicher, 2012). On the other hand, allotment gardens support inherited plant species, instead of the cultivation of engineered hybrids (Speak et al., 2015). These points are important because landscape changes associated with urbanisation tend in general to lead to a decline in biodiversity (Haase et al., 2014). But allotments also promote an active lifestyle. A study from the Netherlands shows that older allotment owners enjoy greater physical health than neighbouring people who do not own an allotment garden (Van den Berg et al., 2010).

However, allotment gardens provide also many important "regulating services": They can reduce the air temperature, especially at night (Farny and Kleinlosen, 1986; Horbert, 2000), and improve air quality if there is no significant release of combustion particles (Langner, 2008). Another important factor is the low sealing degree of allotment garden areas, which accordingly increase the infiltration of rainwater and promote the uptake of groundwater (Farny et al., 1986; Endlicher, 2012). Allotment gardens also offer a considerable pollination capacity (Bell et al., 2016), which can be remarkable higher than in urban parks (Speak et al., 2015).

A very important "cultural service" of allotment gardens is the learning aspect for the children, who learn from the gardens how to deal with nature (Farny and Kleinlosen, 1986; Endlicher 2012). Additionally, allotment gardens promote social relationships (Breuste and Artmann, 2015), are play and communication spaces for children and support interculturality (BMVBS, 2008). Finally, allotment gardenss are also areas in which valuable knowledge such as lost garden culture and gardening knowledge is preserved and handed down (Barthel et al., 2010; Speak et al., 2015). Allotment gardens therewith represent a real cultural heritage.

Summarised, allotment gardens offer not only much green space, they are also an important asset for cities. Thereby positive effects of allotment gardens on the quality of life in the city are often not limited to their own boundaries. The local influence of urban green spaces is one of the most studied UES (Fig. 3 a)). However, the proportion of allotment gardens in UES studies carried out so far is surprisingly low (Fig. 3 b)). By 2014, only 1.3% of 217 included articles of a comprehensive review of UES referred to allotment gardens (Haase et al., 2014). This value is significantly lower than that of parks (4.8%) or green infrastructure (11.7%). These numbers show that for allotments in central European cities such as Berlin, a widespread kind of green space still has a high research potential.

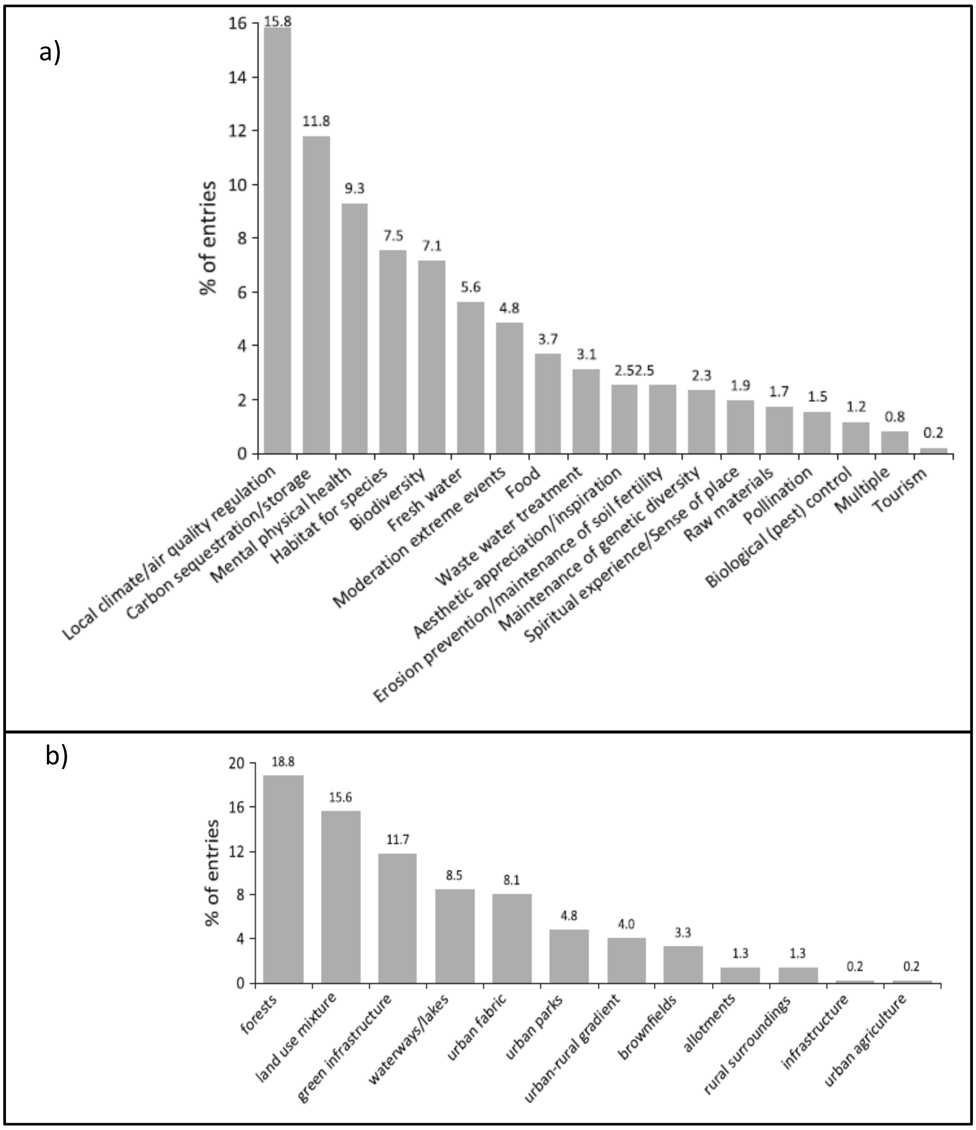


Fig. 3: Relative frequency of the examined types of UES (a)) from the concerning UES providing unit (b)) based on 217 reviewed articles. Source: Haase et al, 2014.

4 Urban climate and the interaction with urban green spaces

As mentioned in the introduction, the UHI of a large city like Berlin with a high population and a relatively high proportion of allotment gardens was an important motivation for carrying out this work. To demonstrate the relevance of the topic, in the first section, the origins of the UHI will be explained in more detail. Based on this, the radiation balance is shown as a cause for the formation of micro-climates in urban areas. Afterwards, the PCI is explained followed by the "park breeze" as an important parameter for microclimatic exchange processes. Finally, a state of knowledge concerning the magnitude of the PCI and the range of the cooling effect, which resulted from the literature research, are presented. Findings concerning allotment gardens on the other hand are presented and discussed detailed in the discussion part.

4.1 Urban climate and the UHI

For a variety of reasons, the climate of a city differs significantly from that of the rural countryside. A typical feature of the urban climate is the formation of an urban heat island (UHI), which results in the urban area by the strong warming during the day and the reduced cooling at night. The urban heat island intensity (UHII) is generally defined by the horizontal temperature difference between the highest urban temperature and the background rural temperature (Oke, 1973). The UHII does generally not increase regularly from the outskirts to the city centre but depending on the surface and the density of the buildings and can also go back across green areas (Fig. 4).

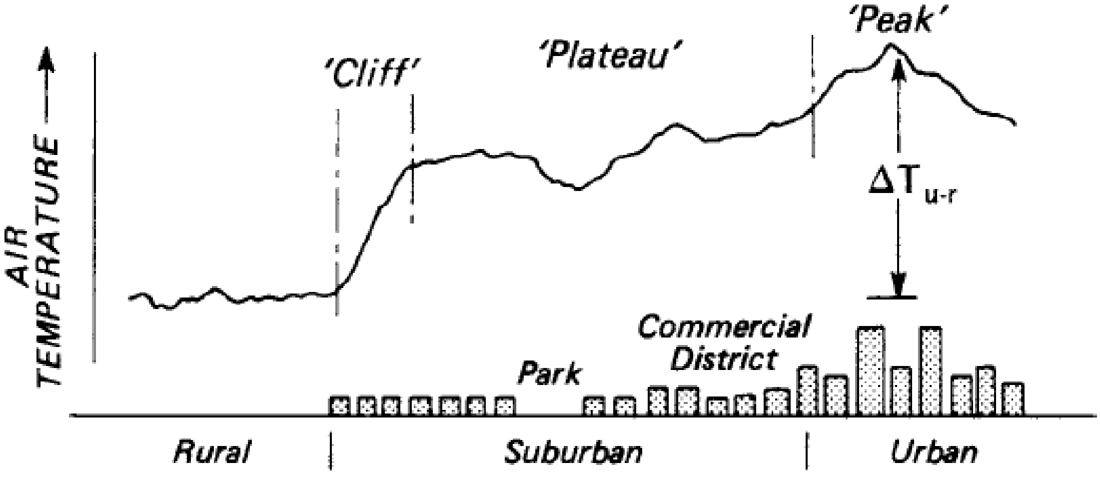


Fig. 4: Scheme of a generalised cross-section of a typical urban heat island with the UHII shown as temperature difference ΔT_{u-r}. Source: Oke, 1987.

The many and sometimes high buildings of a city increase the roughness length of the surface significantly and furthermore form an obstacle layer for the air, which does not occur in this way in the rural surroundings of the city. Accordingly, the Planet Boundary Layer (PBL) as area in which the air currents are subject to the influence of soil friction is divided into two specific layers above the urban area: The Urban Urban Canopy Layer (UCL), which stretches as an obstacle layer from the ground to the mean roof level (Oke, 1986; Pearlmutter et al., 2017) and the adjoining urban boundary layer (UBL), which is influenced by the urban area and its lower boundary (Fig. 5).

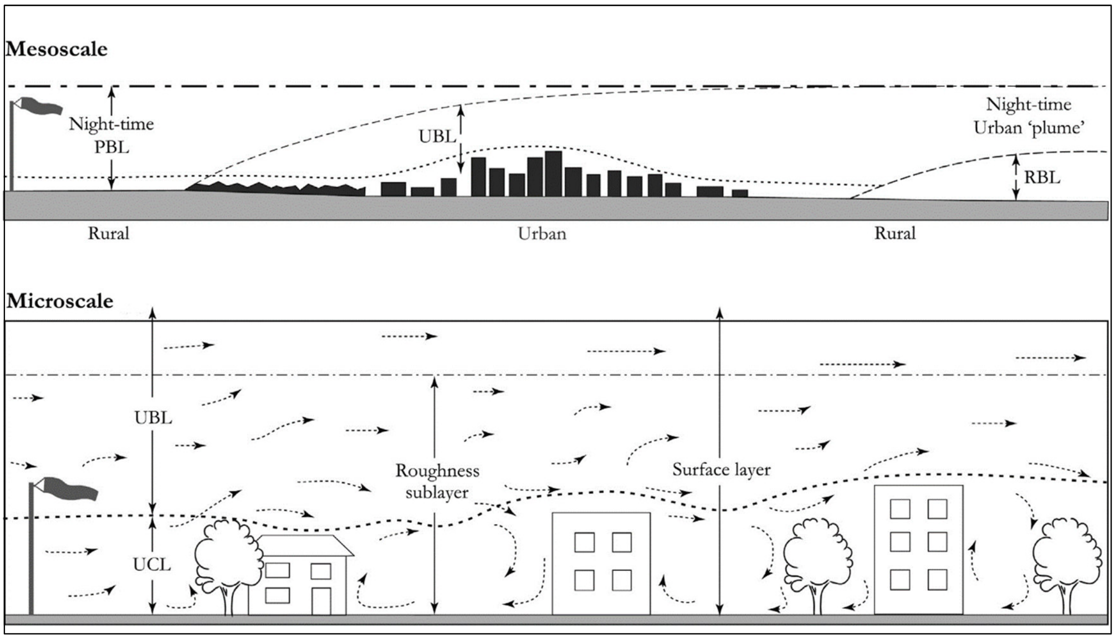


Fig. 5: Scheme of the urban boundary layer (UBL) and urban canopy layer (UCL) during night. Source: Gunawardena et al., 2017.

In the UCL the climate is controlled by micro-scale processes resulting from the interaction of the air within this layer with the immediate environment (buildings, streets, squares, parks) and their physical properties (building orientation, albedo, thermal properties of the building material, moisture content) (Oke, 1976; Ng et al., 2012). Since the UCL is also the area where people live in the city (Gunawardena et al., 2017), the UHI intensity in UCL is most important for the thermal comfort and health of the inhabitants of a city (Pearlmutter et al., 2017). The UHI is most pronounced in the low area of the UCL nearby the ground because in this air layer the energetic

preconditions are most suitable for its development (Matzarakis, 2001) since the interaction with the urban ground is maximal.
The specific local climate of a city is determined by various factors. One of the main reasons for urban overheating is the building development and soil sealing with artificial materials that can store more heat than the original rural landscape due to their high density (Bongardt, 2006). The three-dimensional, enlarged urban surface can absorb a lot of heat energy during the day through solar radiation. Furthermore, the built-in artificial materials usually have a high heat storage capacity (Christen an Vogt, 2004). As a result, urban surfaces absorb significantly more thermal energy during the day than the rural environment. This surplus of energy of urban areas in turn is emitted during night, in general stronger and over a longer time-period than in the rural surrounding. Another key issue that contributes to the emergence of UHI is the multiple reflection of shortwave radiation due to the complex three-dimensional surface geometry of the city and the horizons constriction, which leads to a decreased emission of longwave radiance and keeps heat in the city (Pearlmutter et al., 2017) while the surface which can warm up during daytime can be remarkable greater than in the urban surroundings. In addition, the sealed surfaces reduce the amount of water that evaporate, hence they also decrease the supply of humidity in a city (Potchter et al., 2006). Additionally, reduced wind speeds in the UCL can reduce the turbulent exchange of heat (Matzarakis, 2001) and finally, the UHI can be enforced by anthropogenic heat sources such as heating, industry, air conditioning or traffic which emit additional heat energy to the UCL (Christen and Vogt, 2004).

The magnitude of the UHI also depends on exterior influencing factors. For example, the UHI increases with the size and population of a city (Oke, 1973) and is most pronounced at night during high pressure weather situations (Arnfield, 2003). Other influencing factors are the altitude and the geographic location of a city (Matzarakis, 2001; Pearlmutter et al., 2017). In fact, there is a statistical correlation between the latitude and the maximum measured UHI with the result that the strongest UHI effects occur in mid latitudes (Wienert and Kuttler, 2005).
Due to the described causes, the UHI can reach remarkable dimensions. Literature research showed determined UHI intensities of 11 K for Berlin (Fenner et al., 2014), 12 K for Montreal (Oke, 1973), and 14 K for Moscow (Lokoshchenko, 2014) and confirm the assumption of strongest UHI intensities in mid-latitudes.

4.2 The radiation and energy balance in urban and rural areas

Due to building structures and soil sealing cities are generally less densely vegetated than the rural environment (Christen and Vogt, 2004), which means that less water is available for evaporation. Also, the increased runoff caused by urban soil sealing and drainage of rainwater through the sewer system reduces the amount of surface water available for evaporative transpiration (Grimmond and Oke, 1991; Taha, 1997). Because of this the incoming shortwave radiation becomes converted from the urban surfaces to a greater portion as sensible heat to its environment than in rural areas while the amount of latent heat decreases (Christen and Vogt, 2004; Pearlmutter et al., 2017). Other factors such as the high thermal conductivity and the higher heat storage capacity of the artificial, dense construction materials and the increased surface sizes, which in turn save and emit more heat energy, additionally increase the possibility to increase the release of sensible heat to the city air in the UCL.

Parameters like the sensible and latent heat flux have a significant impact on the formation of microclimates within the UCL. Since the different, surface-dependent energy and radiation balances are responsible for the formation of temperature differences and therefore the formation of the UHI and PCI, they will be considered below. The energy balance of a simple surface can be described with the following equation:

$$Q^{*} = Q_H + Q_E + Q_G \ (1)$$

Though Q^{*} is the net radiation, Q_H the turbulent flux of sensible heat, Q_E the turbulent flux of latent heat and Q_G the heat flux into or out of the material that constitutes the surface. This form of radiation balance can be applied to a rural environment with a simple soil surface and a barrier-free environment (Bongardt, 2006). For urban areas this is not possible because of the complex three-dimensional surface of a city. Since the determination of an uniform heat flux with the many heterogeneous heat fluxes of urban surfaces is not possible, Oke, 1988 defined a size that quantifies the total energy storage within a considered volume, the storage heat flux ΔQ_S, under the simplified consideration of an interface at roof level of the considered urban area. Another term to complement the energy balance of a city is the anthropogenic heat flux density Q_F, which takes the heat fluxes released by combustion processes such as heating or industrial plants into account. Since Q_F is supposed to be a rather small term, it should be negligible during the study period, which was in summer. This simplifies the considered energy balance to:

$$Q^* = Q_H + Q_E + \Delta Q_s \ (2)$$

A comparison of equations (1) and (2) shows that the remarkable difference of the radiation balances between urban and the rural environment is ΔQ_s in the urban area. This storage term covers all the heat energy that streets, houses and other artificial urban materials exchange through their boundary surface with their environment, and for a considered horizontal area ΔQ_s is usually much larger than Q_G (Arnfield 2003). But also Q_H and Q_E differ between city and country. Like described above, Q_E in urban areas is generally lower than in the rural environment, especially in the absence of vegetation and artificial irrigation in the city. A 30-day-lasting study in Basel in the summer months of June and July showed that the average proportion of Q_E during daytime in the radiation balance for inner city areas was about 20%, while in the rural surroundings it amounted a proportion of 60% of the radiation balance, which was three times higher than in the city. The absolute humidity of the city stations was lower by 0.6 g/m³. The city centre was a "dry island", which had a 10% lower total water vapor content than the rural environment (Christen and Vogt, 2004). In contrast, the sensitive heat flow was twice as high in the city during the daytime than in the rural environment. The radiation balance (net wave radiation) of a certain place can be described as the sum of the short-wave radiation fluxes (K) and long-wave radiation fluxes (L):

$$Q * = K \downarrow + K \uparrow + L \downarrow + L \uparrow \ (3)$$

$K \downarrow$ is the global radiation consisting of the direct and diffuse solar radiation. $K \uparrow$ is the reflected short-wave component of global radiation. $L \downarrow$ the longwave atmospheric counter-radiation and $L \uparrow$ is the outgoing long-wave radiation to the atmosphere. The magnitude of the long-wave radiation ($L\uparrow$) of a regarded surface is defined by the Stefan-Boltzmann law (4). Accordingly, the size of $L\uparrow$ of the regarded surface i depends on the emission coefficient εi, the absolute temperature T in Kelvin and the Stefan Boltzmann constant (σ):

$$L_i \uparrow = \varepsilon_i \, \sigma \, T_i \ (4)$$

In contrast to $L\uparrow$, $K\uparrow$ depends direct on the albedo. The albedo of the most Central European cities is low with values from 0.15 to 0.20 (Taha, 1997). In another study of the city of Lodz in Poland even an albedo of only 0.08 was determined (Offerle and

Grimmond, 2003). A study that investigated the energy and radiation balance of Basel revealed albedo values of around 0.10 at representative measurement sites in the city centre and 0.20 in the surrounding rural area (Christen and Vogt, 2004). However, a low albedo results in a high absorption of heat energy, which leads to an increase of $L\uparrow$ compared to the rural environment. Another effect which can lead to an increase of $L\uparrow$ in the UCL for a longer time is the trapping of long-wave radiation in the urban street canyons (Christen and Vogt, 2004). Measurements in the city centre of Basel showed that $L\uparrow$ in the city was 20 W/m² higher in the evening than in its rural surrounding, moreover the evening was the time of the maximal differences between city and rural surrounding area. During this time, the UHI was also on most pronounced (Christen and Vogt, 2004). By the early morning, the difference of $L\uparrow$ dropped to about 10 W/m² and reached its minimum at noon with 5 W/m².

Although the radiation fluxes have not been studied in this work, this part shall provide a background on the processes that lead to the UHI of Berlin and the investigated cooling by allotment gardens. All the described processes and differences in heat flux and heat radiation result in temperature and pressure differences which in turn initialise the development of micro- to mesoscale wind regimes in the city (Bongardt, 2006). This connection is important for the emergence of corridor winds and the so-called "park breeze" (cf. section 4.4), which is important for the distribution of cold air of green areas inside of a city to its adjacent urban neighbourhood.

4.3 Emergence of the PCI

The phenomenon that urban park areas can be colder than their urban surroundings is known since a long time. Already in the 1960s, it was shown that London's Hyde Park was up to 1.7 K colder than its urban surroundings (Chandler, 1965). At that time, the phenomenon did not have its own fixed name. The meanwhile common "Park Cool Island" (PCI) was introduced by Rachel Spronken-Smith in 1994. From this definition the maximum PCI intensity (PCII) describes the difference between the maximum air temperature of the urban neighbourhood of the regarded park (T_n) and the minimal air temperature in the park (T_p) (Spronken-Smith, 1994).

$$PCI = T_n - T_p \quad (5)$$

Nevertheless, the definition of the PCI also changes between different studies, depending on measurement approaches and aims. Appropriately exists also the approach to use the urban maximum temperature T_u as reference for the maximum PCI (Spronken-Smith and Oke, 1998) or the usage of the difference of an average of both parameters of equation (5) (Ren et al., 2013). The formation of the PCI, like that of the UHI, is based on changes in the radiation balance between the two reference areas (cf. section 4.2) and therefore must not be explained again. However, both indices differ in their size as an example of Vancouver shows (Oke, 1989), in which the cooling rates of land, park and city were put together (Fig. 6):

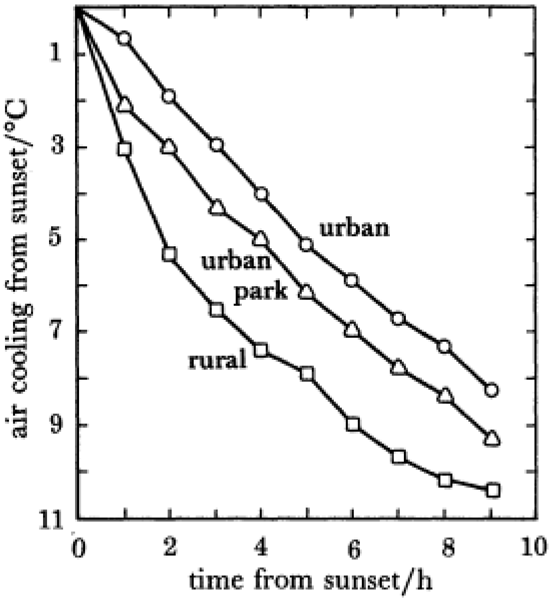


Fig. 6: Accumulated cooling rates of the rural environment of Vancouver, a park in Vancouver and the inner city of Vancouver, British Columbia from a radiation night in August 1971. Source: Oke, 1989.

The main reason for the difference between UHI and PCI is that the park area is surrounded by the urban neighborhood which always interacts with the urban park to a certain degree. It is assumed that due to a compensating flow of the "park breeze" (cf. section 4.4) a flow of warmer air above roof level infiltrates again back to the park (Fig. 7) and therewith limits the cooling of the green area (Oke, 1989).

Ideal conditions for the development of a strong PCI predominate during periods with autochtonous weather with low wind speed and low cloud cover (Borgardt, 2006). Under these weather conditions, the microscale differences in the radiation balance are most pronounced, which is also true for the air temperature because the surfaces have a maximum interaction with the overlying air layer. However, also under these conditions, the PCI can have an impact on its adjacent urban neighbourhood.

4.4 Park breeze

There exist three possibilities that enable the expansion from cold air of an urban park to its adjacent urban neighbourhood: A balancing flow, an entrainment of the cold air with the superordinated wind or a combination of both (Bongardt, 2006).

The most interesting should be the balancing flow since it occurs under weak-wind and almost cloudless conditions and therefore then when the conditions for the formation of a strong PCI and cooling effect are the best. The resulting microscale balancing flow, the so-called "park breeze" is a consequence of the different radiation flows between the park and the surrounding area (cf. sections 4.2, 4.3) which results in a higher cooling rate over the park area compared to the built-up urban environment (Oke, 1989). Caused by the temperature difference between the park and urban area in the UCL also a gradient of air density and air pressure develops with the consequence of higher air pressure and higher air density above the green area than in the adjacent urban area (Bongardt, 2006). Since the air flows in the direction of the lower air pressure, an air flow results which is directed from the park into the surrounding urban area. Thus, over the park area a stable atmospheric layering results nearby ground level, comparable to the rural surroundings (Spronken-Smith and Oke, 1998). Since the development of the PCI is going out from the ground of the green area, the appearance of a PCI results always also in near-ground inversion over the green area (Bongardt, 2006).

In contrast, the high level of sensible heat emitted at night in the urban neighborhood (cf. section 4.2) causes an unstable atmospheric layering in the urban environment of the parks, which is an additional process that enables the formation of a "park breeze" (Gunawardena et al., 2017). This flow circuit becomes closed by an equalising flow above the UCL, which compensates the subsidence of air over the park area (cf. Fig. 7). However, due to the nature of the driving parameters of the park breeze, its generated wind speed is comparatively low. Studies of the existence and above all measurements of the wind speed of this phenomenon are very rare. Though it can be stated out that a park breeze only develops under high atmospheric stability nearby ground level over the source are of cold air and when the temperature difference between the green area and the surrounding built-up area has a sufficient dimension (Thorsson and Eliasson, 2003). Measurements in the study of Thorsson and Eliasson, 2003 indicate that a park breeze can reach a typical wind speed in a dimension of 0.3 m/s. Bongardt, 2006 gives with a hydrostatic approach an estimate of a theoretical park breeze of 0.5 m/s for the maximal temperature difference of 3.8 K measured in the study of Thorsson and Eliasson, 2003 and estimates the same for the maximal PCI of 3.9 K measured in his study. Bongardt, 2006 argued that the actually measured wind speed for this situation was with 0.3 m/s clearly lower above all because of friction influences.

However, the thermal introduced breeze measured by Thorsson and Eliasson, 2003, only developed when the ground of the investigated 10 ha wide surface was snow covered, when a strong ground-based inversion and high stability existed and when the superordinated wind in 10 m height was less than 0.3 m/s. It is also emphasized that a sufficient horizontal air temperature gradient is necessary for the formation of a such a thermal introduced breeze. This argument is proven since in situations in which a thermal introduced wind was measured the horizontal temperature difference at a height of two meter in 2 m was at least 2.5 K (Thorsson and Eliasson, 2003). The study also showed that the thermal introduced wind system only developed seldom under strong stable conditions during winter time, which is interesting since this work investigates the thermal but also wind behavior during summer time.

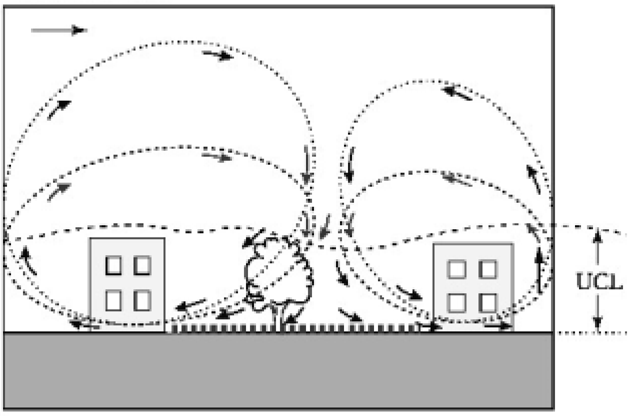


Fig. 7: Scheme of a park breeze for an existing PCI for the day (higher reaching circulations) and for the night (lower reaching circulations). Source: Gunawardena et al., 2017.

To a certain extent, the cold air arising above an urban park can also be displaced into the adjacent urban environment with the superordinate wind field. Consequently, the park air is then transposed into the built-up area leeward of the superordinate wind direction. In Montreal, for example, for a 34 ha wide park under weather conditions with clear sky and a wind speed of approximately 2 m/s, a cooling effect was observed during summer that exceeded several hundred meters leeward (Oke, 1989). However, at a certain wind speed, this advection process becomes again significantly weakened or prevented caused by turbulent mixing of the lower air layer in the UCL with that of the UBL. The critical wind speed, which makes the PCI negligible or lead to its disappearance amounted in a study in Montreal 6 m/s (Oke, 1989) and in a study in Munich 5 m/s (Bründl et al., 1986). Another study in contrast found also an obvious relocation of cold air of different green areas in Berlin at wind speeds between 4 and 6 m/s. These results show that the superordinated wind can on the one hand increase the extend of the cooling effect by a leeward extension of the park breeze circulation system (von Stülpnagel, 1987; Bongardt, 2006), on the other hand it should also be able to interrupt the park breeze, either by modifying the wind direction nearby the ground or by reducing the PCI as cooling source.

4.5 Dimension of the PCI and extension of the cooling effect of urban parks

Because of its importance for the urban climate, the PCI effect has been investigated in numerous studies in various geographic latitudes. In general, the PCII increases with the size of the park area (Barradas, 1991; Bacci et al., 2003). Thereby the PCI of park areas can reach considerable dimensions. In Tucson, Arizona (USA) in the hot and dry desert climate a nightly PCI of 6.8 K could be determined for a 53 ha wide multi-used park in August under weather conditions with low cloud cover and a wind speed of 1.5 m/s (Spronken-Smith, 1994). In Sweden, a PCI of up to 5.9 K could be detected in summer for a 156 ha wide park with mixed, differently distributed vegetation and land cover. A study that examined the PCI in Sacramento, California and Vancouver, Canada showed that the maximum possible PCI for Vancouver was about 5 K in a garden park, and was slightly smaller than the maximum PCI, which was measured in Sacramento with 6.5 K for a dry savanna park (Spronken-Smith and Oke, 1998). In this study, it has been found out that the maximum PCI depends on the surface of the park: Park areas that were mostly covered by trees had the maximum PCI in the afternoon. Garden, multi-use and savannah park types reached the maximum PCI shortly after sunset. Grass-covered open-parks reached the maximum PCI around sunrise. During daytime, the PCI is likely to be mostly caused the evaporation and shade of trees, while open-night parks with dry soils cool the most at night (Spronken-Smith and Oke, 1998). This assumption is supported by results from Israel, in which a 2.8 ha wide, tree-covered park had a cooling effect of up to 3.5 K, which was maximal in the afternoon. Similar results were obtained in a study carried out in Kuala Lumpur in which a maximum PCI of 4–5 K was also reached in the afternoon (Spronken-Smith and Oke, 1998).

However, the PCI is usually not limited only to the area of the park, because the cold air can extend to the adjacent urban environment. Especially large park areas show remarkable cooling extensions. For example, the 156-ha wide Slottsskogen Park in Göteborg, Sweden had a spatial influence of up to 1100 m, which is slightly below the park's average diameter of 1250 m (Upmanis et al., 1998). A similar finding was obtained for a 525-hectare park in Mexico City, which had a cooling effect to a distance of approximately 2 km (Jauregui, 1990–1991). A more recent study from London showed that the PCI of the 111 ha wide multiused Kensington Gardens adjacent to the 146 ha wide Hyde Park can reach maximal 4 K and extend up to 440 m in the urban neighbourhood (Doick et al., 2014).

The effect of smaller parks on their urban environment is in absolute terms less than that of large parks. Nevertheless, the 4.86 ha wide Trafalgar Park in Vanouver displayed high values with a PCI of up to 5 K in summer and a cooling extend of 200–300 m (Spronken-Smith and Oke, 1998; Bongardt, 2006). For the 3.6 ha wide Vasaparken in Göteburg, Sweden, a PCI of up to 0.9 K was detected, with an influence of the park at distances up to 40 m (Upmanis et al., 1998). A similarly high PCI of 1.0 K was determined for the Stadtpark-Steglitz in Berlin (von Stülpnagel, 1987) whereby the cooling influence had and extend between 80 and 140 m. A common finding in literature is that the cooling effect of parks is limited to an extend correspond to its own diameter (Jauregui, 1990–1991; Spronken-Smith and Oke, 1998), which was considered in the measurement approach of this work.

Nevertheless, it must be emphasised that urban parks can also be warmer than their urban surroundings. For example, a study carried out in Tel Aviv, Israel in summer showed that a predominantly grass-covered park was during daytime as much as 1.4 K warmer than its urban environment (Potchter et al., 2006). In the case of grass parks, this warming compared to the urban environment can indeed amount 1 to 2 K even during daytime irrigation due to the absence of shading, (Potchter et al., 2003). One reason for this excessive heating of urban parks during daytime is an elevated surface temperature in the park areas, caused by incoming solar radiation. Aerial surveys showed that the surface temperature of parks in Vancouver without daytime irrigation in summer was comparable to sealed areas in its surrounding (Spronken-Smith and Oke, 1998). Surface temperatures at non-irrigated park sites were thereby 10 K higher during daytime than irrigated areas, whereas at night they could be up to 6 K colder than the moister sites of the park (Spronken-Smith and Oke, 1998). Since the overheated park surface interacts in turn with the air layer in the UCL above, also heating effects of the air within the park area can occur during the day. The local overheating becomes especially clear and measurable when the urban environment corresponding to the calculation of the PCI is itself shadowed (Potchter, 2006). However, the results of another study show that high surface moisture and thereby reduced surface temperatures during the day generally have little effect on the temperature of the air layer above during daytime, due to the turbulent exchange with the urban boundary layer (UBL) (Spronken-Smith, 1994). However, moisture in the soil generally increases the thermal capacity of the ground, which, when the external conditions prevail for it, will attenuate the increase in air temperature over the green area or even lead to a daily PCI. At night, however, this effect attenuates the cooling of the air above the parking area (Spronken-Smith and Oke, 1998). In summary, it can be stated that the PCI depends not only on the park size and the geographic location, but is also influenced by the park type, its vegetation and its water content.

5 Investigation area

This work refers to the results measured in an allotment garden colony in Berlin (52.52° N, 13.40° E), Germanys capital and largest city with a population of meanwhile 3.67 million people (Amt für Statistik Berlin-Brandenburg, 2016). According to the climate classification by Köppen and Geiger, the study area is located in a warm, humid climate with warm summer (Cfb), whereby in summer air temperatures can rise to 38°C (Imbery et al., 2015). Berlin has a spatial extent of about 892 km², with a maximum extent in north-south direction of 38 km and 45 km in west-east direction (Amt für Statistik Berlin-Brandenburg, 2016). The city is relative flat. The built-up area of the city extends on a level between 31 and 70 amsl, with the highest areas in the northeast of the city in the area of the "Barnim-Plateau" and in the southwest of the city on the "Teltow-Plateau". The deepest part of the city is formed by the "Berliner Urstromtal" in the central area of the city. The investigated allotment garden area, the colony Johannisberg, is located in the south of the Berlin district Wilmersdorf, which belongs to the borough Charlottenburg-Wilmersdorf at 52.474°N, 13.313°E (Fig. 8). The district had a total number of 336,249 inhabitants of at the end of 2016, an increase of inhabitants of 8.4% since 2007 (Amt für Statistik Berlin-Brandenburg, 2017) and a population density about 4800 people/km². The average sealing degree of Charlottenburg-Wilmersdorf is 40.6% and therewith above Berlin's average sealing degree of 32.8% (Senat für Stadtentwicklung und Wohnen, 2017). The district is subdivided into a less densely built, locally wooded area in the southwest and in a densely built area in the north and east. The colony of Johannisberg is located in the border area of the inner-city of Berlin (Farny and Kleinlosen, 1987) and therewith in the so-called "Berliner Kleingartengürtel", an area encircling the past centre of the city including allotment gardens, developed especially at the time of the strong population growth of Berlin between 1875 and 1920 (Farny et al., 1986).

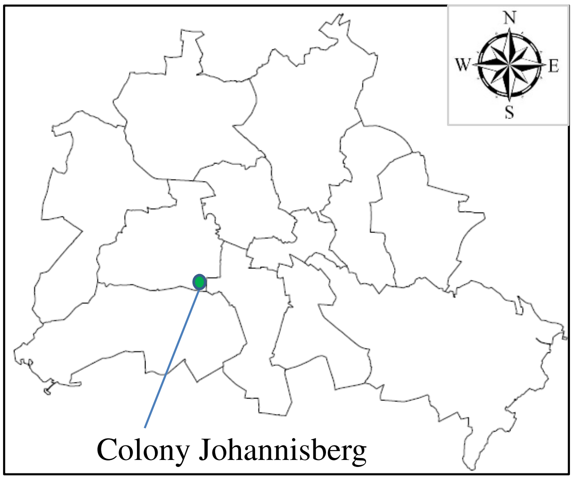


Fig. 8: Position of the colony Johannisberg in Berlin.

The area surrounding the investigation area is relatively flat, with a light descent from northwest to southeast (cf. Fig. 9) Within the colony, there are greater altitude differences. Here, the terrain drops off obvious in the southern part to the southeast. Appropriate, the southeast of the colony is 39 amsl, while the colony area rises up to 46 amsl in the northwest (Fig. 9). In contrast in its central parts, the colony is comparatively flat.

West of the colony Johannisberg adjoins a residential area with predominantly closed perimeter development, which has a height of about 13–16 m and a geometric character. It is separated from the colony by the Johannisberger Straße (Fig. 10), which has together with its sidewalks a width of 15 m. The residential area to the east of the colony is characterized by more open, but with 15–20 m also higher building structures, which belong to the "Rheinisches Viertel" (1910–1914) (Langer, 1993). After a first row of buildings nearly direct adjacent to the colony in the middle colony height follows the Rüdesheimer Straße which enters northward into the Aßmannstraße (Fig. 11). The first has in height of the investigated region together with footpaths and parking lots a remarkable width of 32 m (Geoportal Berlin, 2017). South of the allotment gardens, a more open built-up area exists, where an artificial sports field is located, adjacent to detached houses and a school. Northern of the colony adjoin the large buildings of a dental clinic, together with terraced houses west of it with a mean height of 7–16 m.

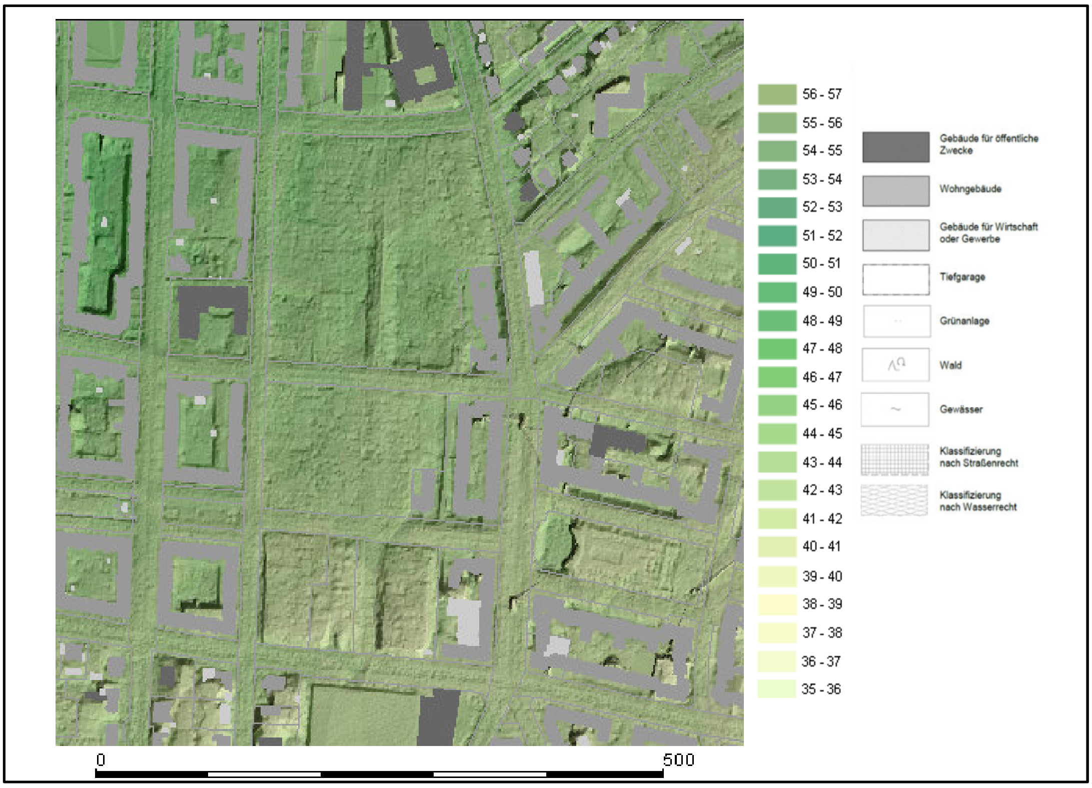


Fig. 9: Surface height in m above mean see level (amsl) in the area of the colony Johannisberg. Source: Geoportal Berlin / [ATKIS® DGM - Digital Terrain Model].

Thus, the allotment garden is surrounded in every cardinal direction by urban built-up area. Relevant adjoining green areas do not exist. In the neighborhood east of the colony the Rüdesheimer Platz is located. The microclimatic influence of this area on the colony Johannisberg should not be significant, firstly due to its separation by houses and a significant elevation on its west side and secondly because of its high sealing degree (Fig. 12). At Eberbacher Straße two green, tree-covered traffic islands adjoin the colony to its west side. Due to their small size, however, they should only have a temperature influence on their direct environment between the buildings. The same was supposed for an almost wooded playground area eastern of the colony in the Homburger Straße. A good impression of the entire investigation area is provided by Fig.11.

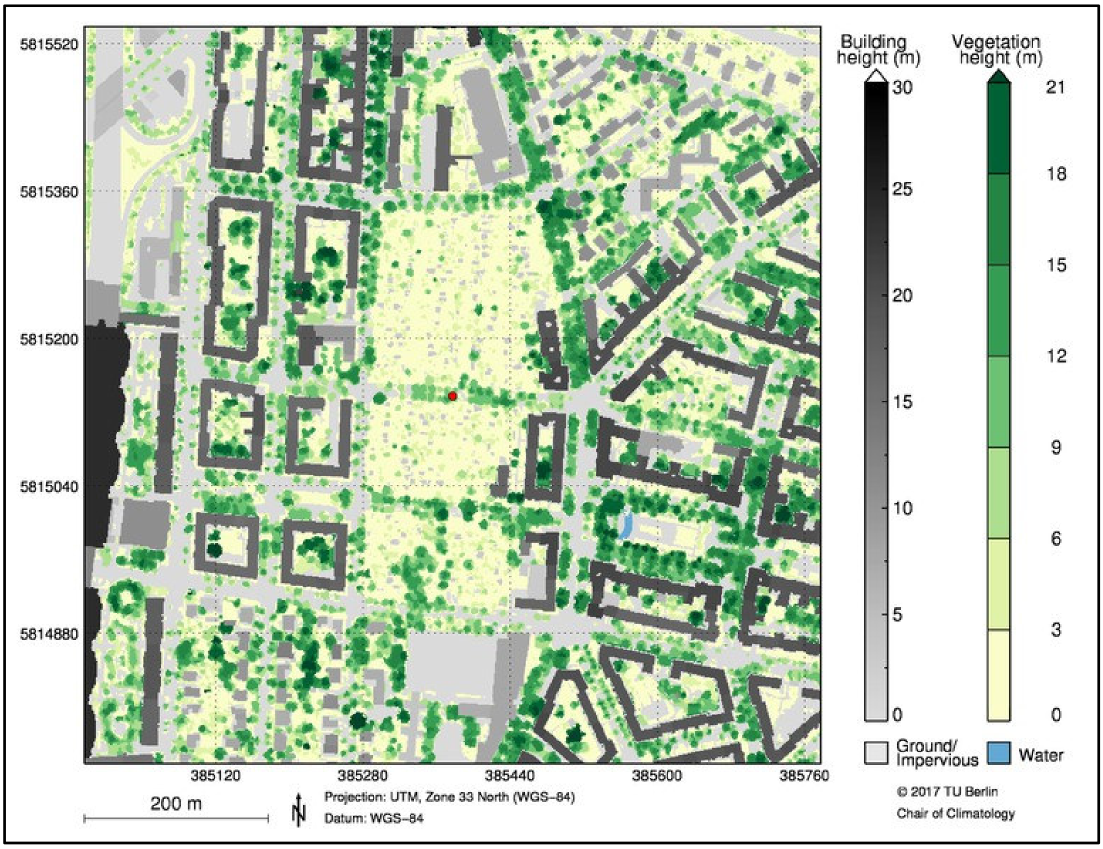


Fig. 10: Building and vegetation height in the study area based on a digital building and vegetation model, resolution 1 x 1 x 1m, Universal Transverse Mercator coordinates projection. Source: Technische Universität Berlin, Chair of Climatology, 2017.

The allotment garden colony Johannisberg was founded on April 1, 1923, comprises currently 235 allotments. The investigated part of the colony covers an area of 65,322 m² (ca. 6.5 ha) and has an approximately extend of 160 m from west to east and 420 m from north to south, (Bezirksverband der Kleingärtner Berlin-Wilmersdorf e.V., 2017). For the colony area an average sealing degree of 15% was estimated. This value is slightly lower than the average sealing degree of 19 %, which was estimated for allotment gardens on Berlin over 30 years ago (Der Senator für Stadtentwicklung und Umweltschutz, 1985). The estimated sealing degree is based on maps of the sealing degree of the Berliner Umweltatlas (Fig. 12) and estimates from on-site visits. The overestimation in Fig. 12 b) in comparison to Fig. 12 a) results because of the counting of the houses at the southeastern edge of the colony into the sealing degree of the colony area due to the calculation in blocks which is only separated here with used streets. However, since the arbours within the colony were all relatively small and the colony paths were mostly only sealed in their midst by plates, a sealing degree of 15% should be a good estimate.

Fig. 11: Aerial view on the colony Johannisberg and its immediate urban neighbourhood. Source: Geoportal Berlin / [Orthophotos 2015 (DOP20RGB)].

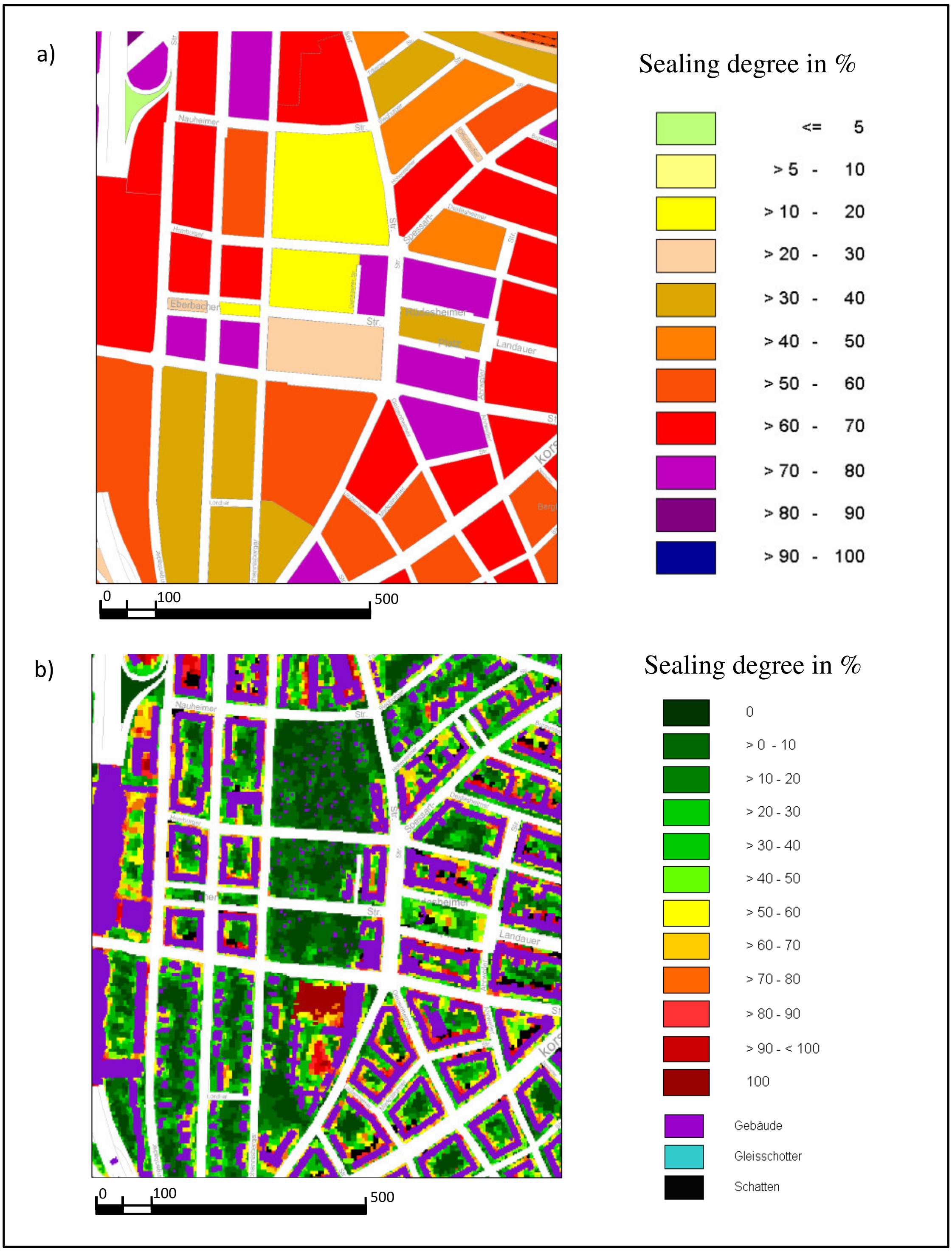


Fig. 12: Block-wise aggregated sealing degree (a) and pixel-wise sealing degree on basis of raster data (b). Source: Geoportal Berlin [Versiegelung 2016, Versiegelung 2016 (uncorrected degrees of sealing, raster data)].

6 Methods

6.1 Search for a suitable investigation area

The first part of the work was the finding of suitable garden colony to answer the question how much the cooling effect is pronounced within the garden colony and to what extent this affects its immediate surroundings. An important basis for the implementation of this work was the booklet “Das bunte Grün – Kleingärten in Berlin“ (Senatsverwaltung für Stadtentwicklung und Umwelt, 2012). This contained, besides general information about the Berlin allotments, also a map showing the distribution of allotment gardens in Berlin (Fig. 13). The map clearly shows that allotment garden colonies are concentrated in the outskirt areas of Berlin. In contrast, in the downtown area allotment garden colonies are rare, what certainly can be attributed to the high density of development in this area. The idea was it to select an appropriate colony which is preferably close to the city centre, firstly because the heat island effect in the inner region of Berlin is more distinct and secondly, due to the higher average density of building development. Accordingly, in the inner part of the city more people would have a greater benefit from the supposed cooling effect by the colony that had to be investigated.

To select appropriate allotment gardens in the inner area of the city, a circle with a radius of 8 km, starting from the central Friedrichshain-Kreuzberg, was constructed. The aim was to exclude the colonies in the border area of the city and to identify areas of allotment gardens that are as close as possible to the urban core.

The next step was to choose the areas of allotments with the greatest spatial extend inside the restricted area, because for these a greater cooling effect is suspected, analog to the findings respective to urban parks (Barradas, 1991). Subsequently, the second limitation criterion was that these colonies within the circle should be as close as possible to the centre of Berlin and an overlay with other green areas should be avoided. Thus, garden colonies were excluded that were superimposed by one or more directions from other large green spaces in their surroundings. Based on these criteria, six different colony areas in the city were selected (Fig. 13). After accurate observations with Google Earth and on-site visits some selected regions had been however again discarded. This affected the colony Abendrot in the south of the defined city centre (Fig. 13), which was mainly because contrary arrangement to previous assumptions. Thereby the colony was primary between open commercial and industrial areas in the south, west and east and other garden colonies in the north. The same applied for the selected southeastern part of an association of garden colonies in the border area of Neukölln and Treptow-Köpenick. Also, the selected colony association in the northwest of the city turned out as unsuitable, because of its proximity to the big park area Jungfernheide and Tegel airport. For this reason the areas labelled in Fig. 14 had been chosen.

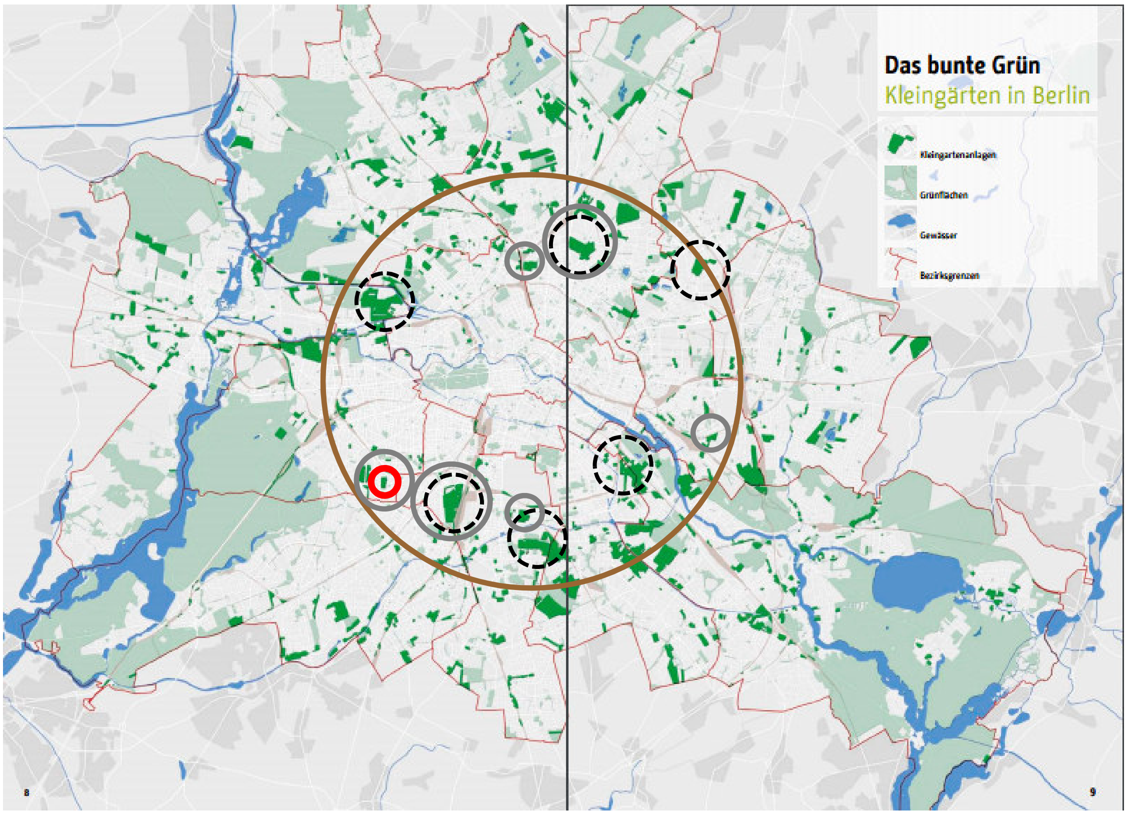


Fig. 13: Allotment gardens in Berlin (dark green areas). The big brown circle surrounds the inner area of the city. The six dotted circles mark the originally planned study areas. The grey circles indicate the areas of allotments that turned out as appropriate. Colony Johannisberg as finally chosen area for investigation is marked by a red circle. Source: Senatsverwaltung für Stadtentwicklung und Umwelt, 2012.

Nevertheless, the resulting six colony areas (Fig. 14) were too much for realisable field measurements. After comparison of the initially chosen potential areas of investigation, colony Johannisberg was chosen. Reasons for this decision were the high portion of residential buildings in the surrounding of this allotment garden area, especially in comparison with the colonies Lebensfreude and the colonies Grüne Wiese and KGA Heinersdorf. Furthermore, the comparative simple geometrical structure, the existence of buildings in every cardinal direction and the streets, which surround the whole colony and also cross it on two sections were arguments that led to the decision to choose the colony Johannisberg as investigation area.

Figure 14: Initially planned study areas in Berlin. a: colonies at the Südgelände (district Schöneberg), b: colony Lebensfreude (district Tempelhof), c: colony Johannisberg (district Wilmersdorf), d: colonies Bornholm I+II (district Prenzlauer Berg), e: colonies Grüne Wiese and KGA Heinersdorf (district Heinersdorf), f: colonies Gute Hoffnung and Hochspannung (district Lichtenberg). Source: Google Earth.

6.2 Measurement scheme

The measurements with the fixed sensors form the basis for this work. In the following the originally planned measurement scheme in the investigation area will be explained and afterwards the preparations for the measurements and its implementation.

6.2.1 Measurement scheme for fixed sensors

To obtain usable and meaningful results, a specific, geometrically uniform measuring scheme was planned for the study area. For the implementation of the study nine DK390 HumiLog „rugged“ sensors were available. Four of these sensors were used outside the colony and fixed along Homburger Straße to obtain a west to east temperature gradient that can be easily combined with mobile measurements. The remaining five of the nine sensors were used for measurements inside the colony, one respectively in each cardinal direction and one in the central part of the colony. The measurement concept with five sensors within the colony should give a more representative picture of the temperature of the total area, which is 6.5 ha wide and should also enable the measurement of temperature differences relating to the border area of the colony. Since in the planned measurement concept three sensors within the colony were located at the height of Homburger Straße, this approach had the additional advantage of including the north and south border areas which were respectively located approximately 200 m from the colony centre. The potential measurement sites for the measuring instruments to be installed were initially estimated per Google Earth. Since street trees provide a good possibility to attach measurement sensors, the sensors should be fixed on suitable trees along Homburger Straße. Thereby the sensors should be orientated northward and therewith in the direction of maximal shade, because the sensors had no artificial ventilation. Furthermore, the sensors outside the colony should be preferably mounted on the south side of Homburger Straße, where the houses southern of the Homburger Straße cause additional shadow. The sensors should be fixed on trees at a height of 2.5 m at a distance of 80 and 160 m to the west and to the east from the corresponding west and east colony border.

The adherence of these distances had three reasons: Firstly, street-trees were available quite accurately at distances of 80 and 160 m wet and east of the colony. Secondly, literature specifies an extend of the cooling effect of urban parks, reaching approximately one park-width (Jauregui, 1990–1991; Spronken-Smith and Oke, 1998) and finally, the consistent distances to the west and east should facilitate the comparability of the measurements.

6.2.2 Preparation and implementation of the measurement campaign

In order to successfully implement the planned measurements in the study area, the Grünflächenamt Charlottenburg-Wilmersdorf was asked beforehand for permission to fix the sensors on to the street-trees in the Homburger Straße. Furthermore, a meeting was held in April with the chairman of colony Johannisberg, in which the purpose and background of the work were presented and explained. The project was afterwards presented by the chairman in the annual general meeting of the colony so that the concerned allotment gardeners were informed about the forthcoming measurements.

For the measurements nine DK390 HumiLog „rugged“ sensors of the company Driesen + Kern were provided, each with a matching white, air-permeable radiation shield. The sensors measure air temperature with a measuring accuracy of ± 0.3 K.

Before the measuring campaign, a calibration for the sensors was done by the Department of Climatology at the Technical University. The resulting gain and offset values for the measured temperature ($T_{measured}$) were respected in the preparation of the measurement data with formula (6). The therefore used offset- and gain-values are summarised in Table 1:

$$\mathrm{T}_{corrected} = (T_{measured} - \text{offset}) \,/\, \text{gain} \quad (6)$$

Table 1: Offset and gain values resulting from the data calibration

sensor	date	offset	gain
DK208	25.04.2017	-0,61963	1,0283221
DK209	25.04.2017	-0,56023	1,0363757
DK211	25.04.2017	0,007771	1,0079385
DK216	25.04.2017	-0,13129	1,0159012
DK217	25.04.2017	-0,94069	1,035904
DK218	25.04.2017	0,023404	0,9984811
DK219	25.04.2017	0,08119	1,001144
Dk220	25.04.2017	0,01956	1,0020778
DK221	25.04.2017	0,162533	0,9990074

One day before the affixing of the sensors, they were activated by the software InfraLog, whereby measurement time scale was set to Central European winter time UTC+1, respectively CET. Afterwards all battery voltages of the sensors were controlled once again. Finally, the sensors were installed along the Homburger Straße, were they were mounted on May 30, 2017. Based on the planned measurement scheme, the sensors were mounted on trees in the area nearby the aspired 80 and 160 m from the border of the colony in western and eastern direction.

In order to be able to keep these distances as accurately as possible also east of the colony, the farthest sensor DK208 was placed there on the northern side of the road protected from sun radiation by treetops. The distances of the sensors were checked by field measurements with a 50-m-measuring-tape, whereby the distances from the colony-borders to the centre point straight below the sensor was measured. All sensors were fixed with cable ties at a height of 2.5 m above the ground on the selected trees. This height should be a good compromise between a reduced risk for theft of vandalism and a level which is still nearby the relevant height for pedestrians and measurement heights of comparable works, which range mostly between 1.5 and 2.5 m (Fary and Kleinlosen, 1986; von Stülpnagel, 1987; Bongardt, 2005; Doick et al., 2014; Al-Gretaweeet al., 2016). To minimize the risk of damage on the trees caused by the cable ties, all trees were wrapped by sheets. The consistence in sensor height and sensor orientation over the complete study area should additionally increase the comparability of the sensors.

On Mai 31, 2017 the remaining five sensors were mounted inside the colony Johannisberg. Thereby the desired spatial distribution presented in section 6.2.2 (Fig. 15) could be realised nearly completely. All sensors could be mounted at a height of 2.5 m, similar to those along the Homburger Straße in northward orientation and also on trees to reduce failures due to daily solar radiation. The sensors on the northern, southern, western and eastern side of the colony were all nearby the colony border of the appropriate cardinal direction (cf. section 6.2.2). Caused by the heterogeneity of the gardens, tree species and height varied. Accordingly, the sensors were mounted on plum trees in the north and west and on cherry trees in the east and south and a lilac tree in the centre region of the colony. Because there were no trees directly at the colony borders and these were also covered by hedges, certain distances resulted between the colony borders and the place of the sensors inside the colony. Another reason was to prevent the sensors for theft in case they would have been mounted for example on metal rods direct on the colony border. These distances to the borders are listed in Table 2, which also contains new names for the sensors, used in the following for an easier classification. Fig. 15 gives an overview over the position of all measurement sites. In this work the measurement results in the western and eastern border region are regarded to be the same at the border, whereby the resulting distances to the west and east of 6.6 and 9.9 m are neglected for simplification. This should be appropriate, since such kind of approach was realised meanwhile in greater dimensions (Farny and Kleinlosen 1986; Doick et al., 2014). Furthermore, for smaller green areas a buffer zone outside the green area has been reported, in which no appreciable cooling effect existed (Shashua-Bar and Hoffmann, 2000), which had a mean extension of 5.6 m. Accordingly the measurements which were realised 6.6 and 9.9 m from the real border of the colony should be representative, especially at night when direct sun radiation is absent.

The sensor in the centre of the colony was mounted on a lilac tree which seemed to be suitable because of its height, vertical structure and position only 1 m form the border between the colony and the pavement of the Homburger Straße. The sensors in the western and eastern border area could be fixed in distances under 10 m from the Homburger Straße (Table 2). These relative small distances should ensure a comparability of the fixed and mobile measurements and even more improve the accessibility of the temperature gradient along the Homburger Straße. Generally, the usage of trees inside and outside of the colony should increase the comparability of the measurement results, also when the height and species of the trees varied.

Table 2: Overview over the measurement sites for the nine used fixed sensors and the new names of the sensors used in this work for an easier classification

sensor	new name	position	distance from colony border	tree species	tree height (m)
DK 208	**EAST_160m**	Homburger Str. / playground	161.4 m (east)	Maple tree	10.0 m
DK 209	**EAST_80m**	Homburger Str. / Rüdesheimer Str.	78.0 m (east)	Plane tree	16.0 m
DK 211	**WEST_80m**	Homburger Str.	80.9 m (west)	Maple tree	11.0 m
DK 216	**WEST_160m**	Homburger Str.	157.9 m (west)	Maple tree	13.0 m
DK 217	**SOUTH_CB**	Southern colony border	-15.9 m (south)	Cherry tree	6.0 m
DK 218	**CC**	Colony centre	-80.0 m (W/E)	Lilac tree	3.5 m
DK 219	**WEST_CB**	Western colony border	-6.6 m (west)	Plum	3.5 m
DK 220	**EAST_CB**	Eastern colony border	-9.9 m (east)	Cherry tree	6.5 m
DK 221	**NORTH_CB**	Northern colony border	-1.5 m (north)	Plum	6.0 m

The used sensors were checked regularly during the measurement period. The sensors were read out once a week at Homburger Straße to save data. In the gardens, the patrols were depended on the presence of the allotment holders, accordingly, they were carried out a little more irregular and mostly on two different days a week. Overall, the sensors hang on the trees for more than one month and the measurements ran without significant complications. The complete measurement period with all sensors ranged from the afternoon of May 31, 2017 until the morning of July 2, 2017, enabling the investigation of a 32-night-lasting study period.

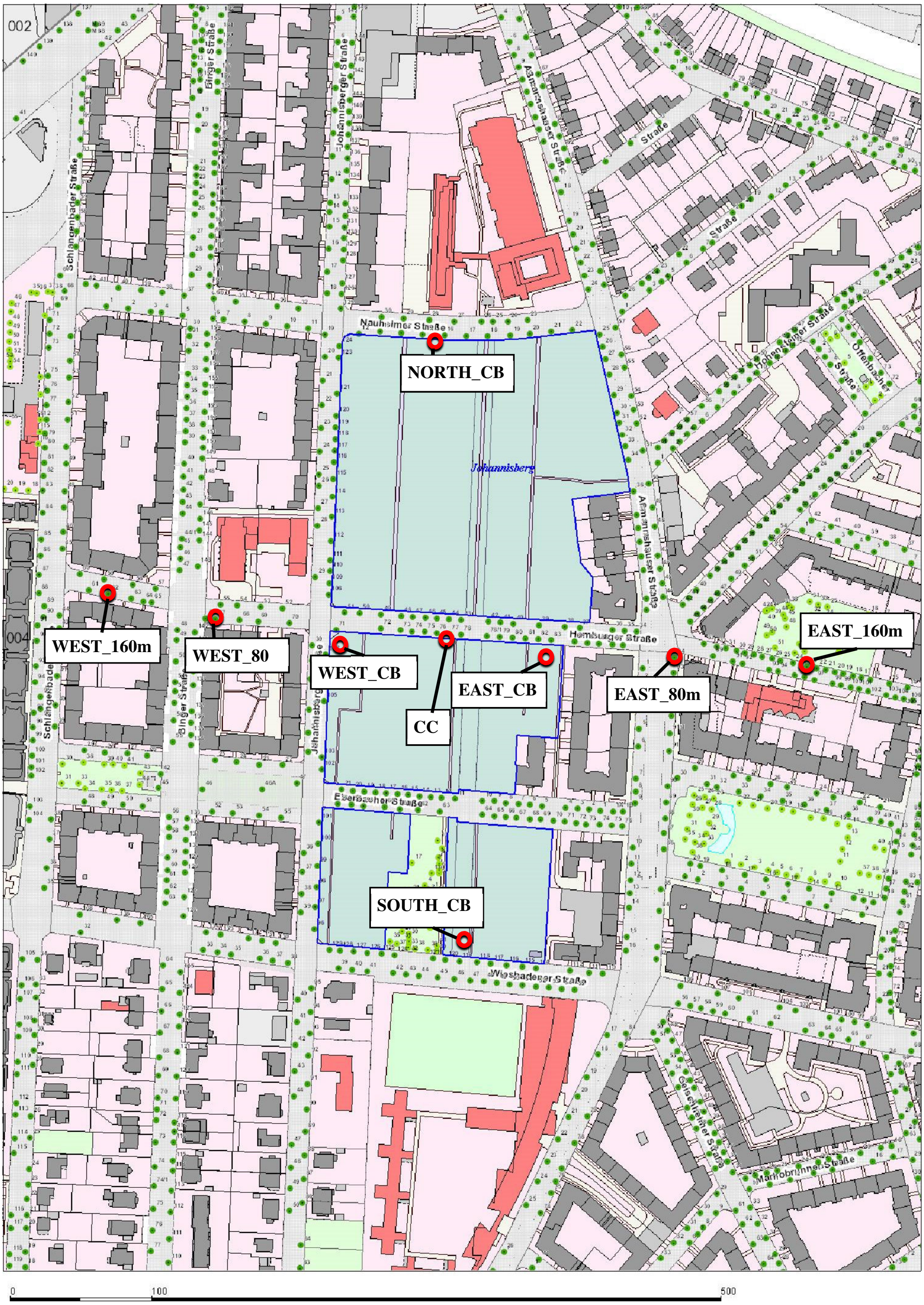


Fig. 15: Overview of the study area with the location and name of the used sensors. Source: Geoportal 2017 [Baumbestand Berlin, ALKIS (Amtliches Liegenschaftskatasterinformationssystem) Berlin].

6.3 Mobile measurements

In this work, the stationary long-term measurements were complemented by mobile measurements with three objectives: Firstly, the mobile measurements should measure between the fixed sensors and increase the spatial resolution of the measured air temperature along Homburger Straße. Secondly, the measurements of the sensors should be compared with the mobile measurements to determine to what extent measurements along the Homburger Straße are comparable with those of the fixed sensor inside the colony near the Homburger Straße. Thirdly, the wind speed and direction along the Homburger Straße nearby ground-level should be determined.

6.3.1 HuMVe

The HuMVe (Human Meteorological Vehicle) is a mobile measuring device of the Institute of Climatology of the Technische Universität Berlin. It has a large brown box in which the datalogger is located. For the measurements of this work the HuMVe was constructed in a certain way (cf. Fig. 16). The radiation equipment for the short-wave and long-wave radiation fluxes as part of the set, was installed in the longitudinal direction to better get through narrow areas such as car gaps. The wind was measured at a height of 3.0 m with a WindMaster 3D ultrasound anemometer. Air temperature and relative humidity were recorded at a height of 2.5 m, similar to the fixed sensors. Table 3 gives an overview of the sensors used at HuMVe and the measuring accuracy.

Table 3: Used measurement instruments, their accuracy and the measurement height

name of instrument	measurement size	resolution	accuracy	measurment height
3D ultrasound anemometer WindMaster	wind speed	0.01 m/s	1 % - 1.5 %	3.0 m
3D ultrasound anemometer WindMaster	wind direction	0.1 or 1 °	0.5 ° - 2.0 °	3.0 m
CS215	air temperature	0.01 °C	±0.3 °C	2.5 m
CS215	relative humidity	0.03 %	±2.0 %	2.5 m

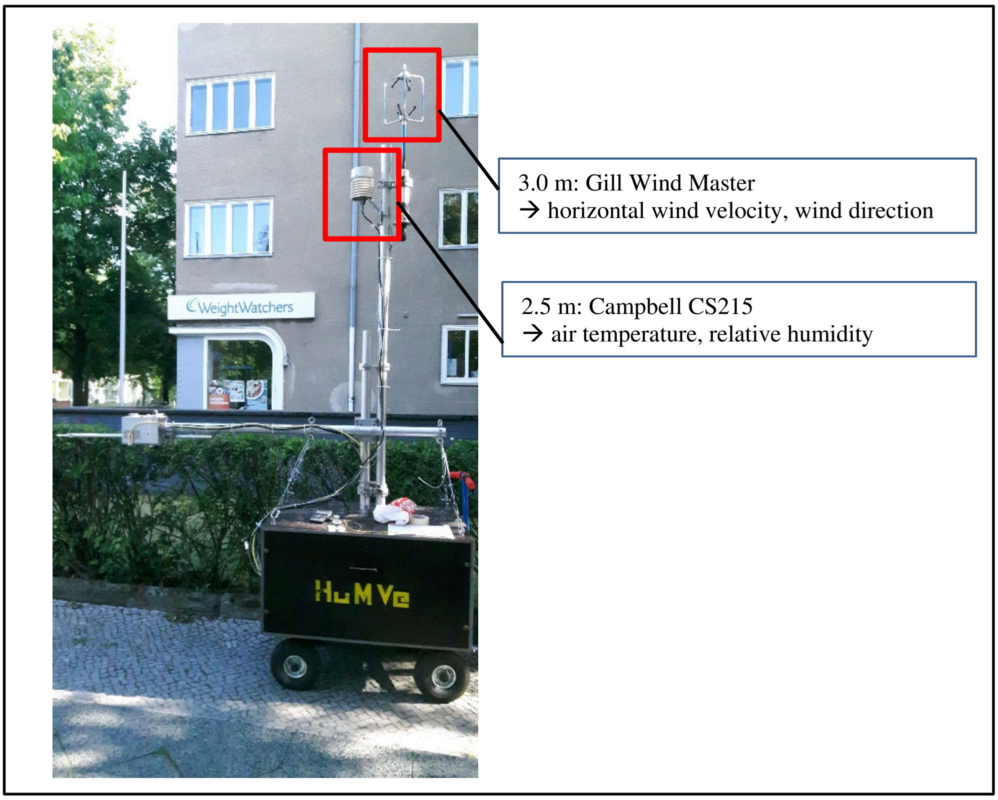


Fig. 16: Composition of the used HuMVe measurement device.

6.3.2 Implementation of the mobile measurements

The mobile measurements with the HuMVe should be made on one day with conditions as autochthonous as possible. Another criterion for the measurements was that they should ideally be done at day and night of a hot day with a maximum temperature above 30 °C in the study area. Thus, for the subsequent night not only easily measurable temperature differences can be assumed, it was moreover possible to study a night in greater detail, in which the reduction of heat stress is particularly important for the population of Berlins inner city-area. The corresponding weather conditions finally occurred from June 19 to June 20. During the day maximum temperatures of up to 33.4 °C were reached in the study area and the day was almost sunny with 15.2 h of sun. In the subsequent night it was nearly cloudless and calm with a mean total cloud cover of 1/8 and a mean wind speed of 1.1 m/s in a height of 10 m above ground. In this time-period, five one-hour-lasting measurement runs were carried out in intervals of 3 hours within the time-periods 13–14 CET, 16–17 CET, 19–20 CET, 22–23 CET, and 1–2 CET.

The measurements were carried out from east to west. The reason for this was that the eastern part of the study area was closer to the HuMVe's pound area. This reduced the risk of a delayed start of the measurements in case of unexpected incidents on the way to the measurement route (Fig. 17). At each of the 13 measuring locations (Fig. 17) the HuMVe was placed in the correct position for 3 minutes. From each of the 3-minute-lasting records, the last two minutes were taken for further data analysis. The previous minute was left so that the temperature of the air inside the radiation shield could adapt to the outer conditions. A further measure to guarantee a faster adaption of the air temperature at the CS215 sensor to the conditions outside the radiation shield was the usage of artificial ventilation also during night. The 13 used measurement sites showed together with the corresponding fixed minutes per measurement traverse are shown in Table 4. After the first measurement run, the previously scheduled time-period of the measurement run at point 9 had to be shifted by one minute from the minutes 37–39 to 38–40. Reason was that the planned detour-rout around a branch barrier on the used sidewalk had to be enlarged because of additional parking cars. Therefore, the original 2-minute distance within the colonies for the measurements here was increased to three minutes for the following four measurements (see Table 4).

Table 4: Overview of the measurement sites with corresponding time periods (columns 1 and 2), the distance of the measurement points to the colony borders (column 3) and distance of the fixed sensors to the measurement route along the Homburger Straße (column 5).

Measure-ment point (number):	**Time span of measurement in minutes of concerning hour:**	**Position in the measurement route to concerning colony border:**	**Levelled with fixed sensor:**	**Deviation of the fixed sensor from the measurement route:**
1	01-03	157.9 m east	EAST_160m	0.5 m
2	06-08	118.0 m east	-	-
3	11-13	78.0 m east	EAST_80m	0.5 m
4	16-18	39.0 m east	-	-
5	21-23	0.0 m east	EAST_CB	12.2 m
6	25-27	-40.0 m east	-	-
7	29-31	-80.0 m east/west	CC	2.2 m
8	33-35	-40.0 m west	-	
9	38-40 (primary 37-39)	0.0 m west	WEST_CB	8.8 m
10	43-45	40.5 m west	-	
11	48-50	80.9 m west	WEST_80m	1.5 m
12	53-55	119.4 m west	-	
13	58-00	157.9 m west	WEST_160m	1.7 m

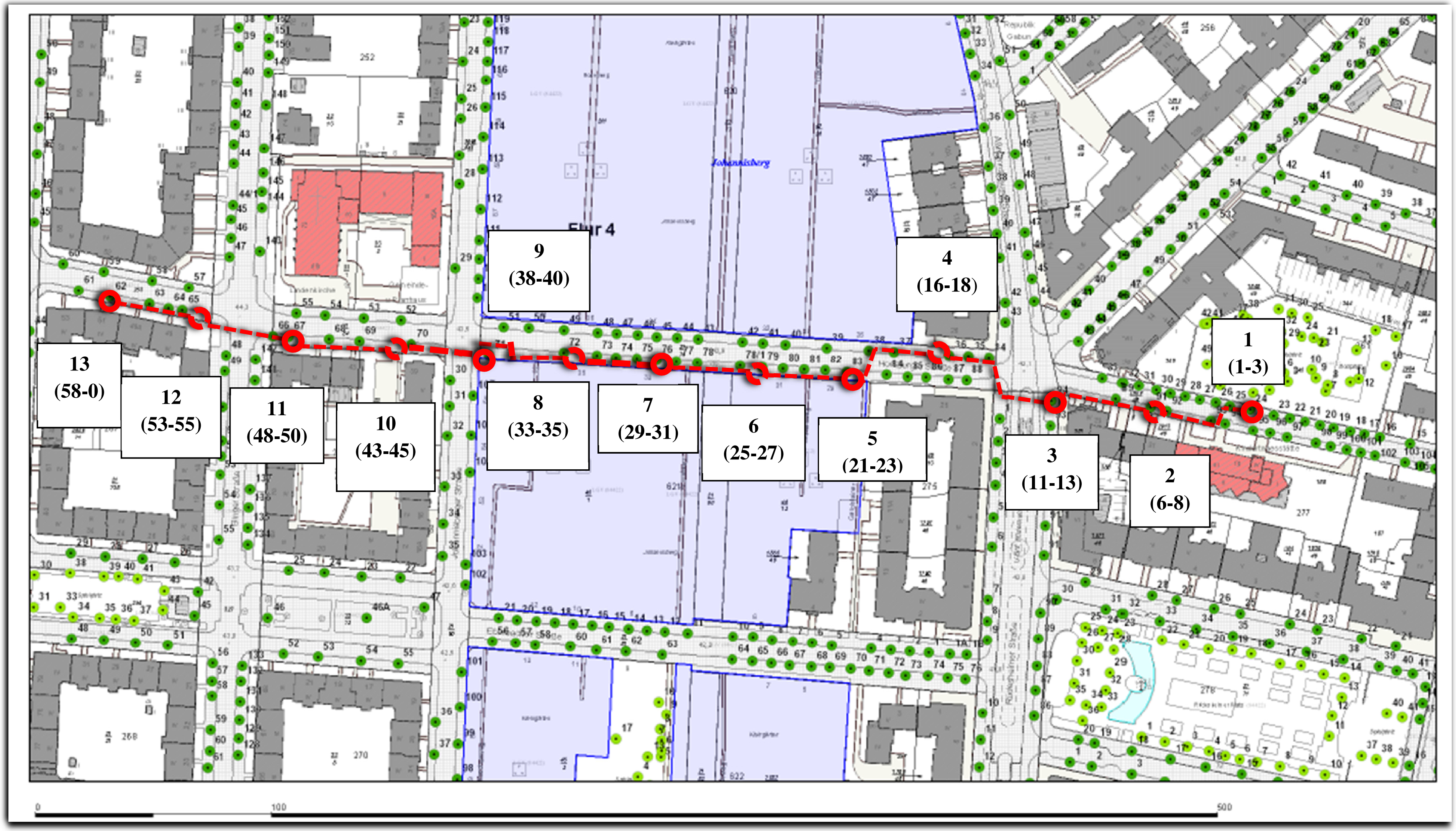


Fig. 17: Position of the measuring points of the mobile measurements with the HuMVe. Red continuous circles: Measuring points at the same distance as the fixed sensors. Red broken circles: Additional measurements between the stationary sensors. White boxes: Number of the measuring point and in brackets minutes of the hourly measuring cycle. Source: Geoportal 2017 [Baumbestand Berlin, ALKIS (Amtliches Liegenschaftskatasterinformationssystem) Berlin].

In order to be able to compare the measured data of the HuMVe with those of the fixed sensors best as possible, the HuMVe was at every point parked at the same distance to the west and east colony border as the fixed measuring devices and therewith at one level with it. Secondly, the HUMVE was placed as close as possible to the fixed reference sensors. Thereby it measured always at Homburger Straße to be additional a useful reference to estimate differences in the cooling effect in the colony and in the area of the Homburger Straße.

For every measurement point a timely buffer of approximately 30 s was considered to put the HUMVE in the right position and adjust it northward for the wind-measurements with a compass. Special features during the measurement traverses were written down and could be incorporated into the work. The two most important points were that the colony was no longer hit by solar radiation in the study area after 20 CET and that at measurement point 10 a wind could be observed, strong enough to move the tree branches of a small tortured willow around the measuring point, while on the other, mostly acer tress around this point no air movement was observable.

After each of the five measurement passages, the batteries for the ventilation of the datalogger were disconnected from the unit to minimize discharge. The three batteries which were provided from the Chair of Climatology of the Technische Universität Berlin were regularly changed and charged at the clubhouse in the southeast of the colony. The artificial ventilation was also activated at night to speed up the response of the temperature sensor of HuMVe to the changing external environment.

6.3.3 Temporal correction of mobile measurements

Because the mobile measurements could not be implemented simultaneously on different measurement points, the temperature measurements were extrapolated to the time steps at the end of each measurement traverse. Therefore, the cooling rates of the fixed sensors were used. The approach was that the measured temperature of the HuMVe measurements was corrected by adding the mean temporal temperature change of the fixed sensor in the same height, which occurred between the measurement with HuMVe at the time of measurement at this point and the end of the HuMVe measurement traverse. For the additional mobile measurement points between the fixed sensors (P2, P4, P6, P8, P10, P12), the average of the cooling rates of the fixed sensor behind and in front of the HuMVe measurement point were used. The approach is described in the equations (7, 8) with i and j as the minutes of mobile measurement and k as the hour for extrapolation at point number l with formula (7) for uneven l and formula (8) for even l numbers:

$$T_{(l)\ (k:00\ CET)} = \overline{T_{HumVe\ (l)\ (k-1:i\ CET,\ k-1:j\ CET)}} + \overline{\Delta T_{fixed\ sensor\ (l)\ (k-1:i\ CET,\ k-1:j\ CET)}} \tag{7}$$

$$T_{(l)\ (k:00\ CET)} = \overline{T_{HumVe\ (l)\ (k-1:i\ CET,\ k-1:j\ CET)}} + \left(\overline{\Delta T_{fixed\ sensor\ (l-1)\ (k-1:i\ CET,\ k-1:j\ CET)}} + \overline{\Delta T_{fixed\ sensor\ (l+1)\ (k-1:i\ CET,\ k-1:j\ CET)}}\right)/2 \tag{8}$$

However, to visualise the application of formula, an example should be made for measurement point P1 and P2 for the last time step 2:00 CET:

$$T_{P1\ (02:00\ CET)} = \overline{T_{HumVe\ (P1)\ (01:02\ CET,\ 01:03\ CET)}} + \overline{\Delta T_{fixed\ sensor\ (P1)\ (02:00\ CET-01:02\ CET,\ \ 01:03\ CET)}} \tag{9}$$

$$T_{P2\ (02:00\ CET)} = \overline{T_{HumVe\ (P2)\ (01:07\ CET,\ 01:08\ CET)}} + \left(\overline{\Delta T_{fixed\ sensor\ (P1)\ (02:00\ CET-01:07\ CET,\ \ 01:08\ CET)}} + \overline{\Delta T_{fixed\ sensor\ (P3)\ (02:00\ CET-01:07\ CET,\ \ 01:08\ CET)}}\right) / 2 \tag{10}$$

6.4 Observational data from other stations

Another important point in carrying out this work was the integration of additional observational data. For this purpose, temperature data of the city climate measuring network (Stadtklimamessnetz-Berlin) of the Technische Universität Berlin were used. With them, it should be possible to determine the UHII and the local temperature differences between the measuring points in the investigation area and the rural surroundings of Berlin. For this purpose, the climate station "Dahlemer Feld" was used (52.4777 ° N, 13.2252 ° E, 56 m amsl), which is located on a large open space in the Grunewald, a wide forest area adjacent to the southwestern part of the city. The station is separated from the city by the forest Grunewald and is located 5.9 km west of the centre of the colony (Fig. 18). The surrounding area of the station is on a wide free space and typically rural with tall grass and separate trees that dominate the landscape. The site was already classified according to the scheme of local climate zones of Oke and Stewart, 2010 as LCZ B “scattered trees” by Fenner et al., 2014.

Another additional station used for this study is the station "Bamberger Straße" (BS), which is located 3.0 km northeast of the colony Johannisberg (52.4964 ° N, 13.3375 ° E, 36 amsl). It should indicate the maximum possible temperature and thus the maximum UHI in the study area without a cooling effect of the colony. The station is characterized by perimeter block development from the Gründerzeit with building heights of about 20 m. The area around the station BS is also characterised by many street trees and small front gardens within the street itself. Since the built-up urban neighbourhood of the colony Johannisberg and around the station BS are quite similar, both can be categorised as local climate zone 5 “open midrise” (LCZ 5). Thus it was assumed that the temperature values of the BS reference station are well suited to estimate the maximum possible temperature around the colony and therewith the cooling effect of to the colony.

In order to be able to additionally include meteorological parameters such as the superordinated wind in the work, hourly data from weather stations of the German Weather Service (DWD) were obtained from the Climate Data Centre of the DWD. Cloud cover data used in this work is from the station Berlin Dahlem, which is located 1.8 km south of the study area, thus providing the closest spatial meteorological data for the study area. The wind data of the station Dahlem were not used, because the wind is measured 26 m above the ground and due to the location of the station on a hill in a total height of 90 amsl, 48 m above Homburger Straße. Instead, the station Berlin-Tempelhof was chosen, which is located 6.5 km east of the study area and where the wind is measured 10 m above ground (48 m amsl). Since the survey is based on hourly data and focuses primarily on cloudless, dry weather conditions with low wind speed during night, despite of the spatial deviation of the wind measurement area, acceptable results are assumed, facilitating the transferability of the study approach to other major cities.

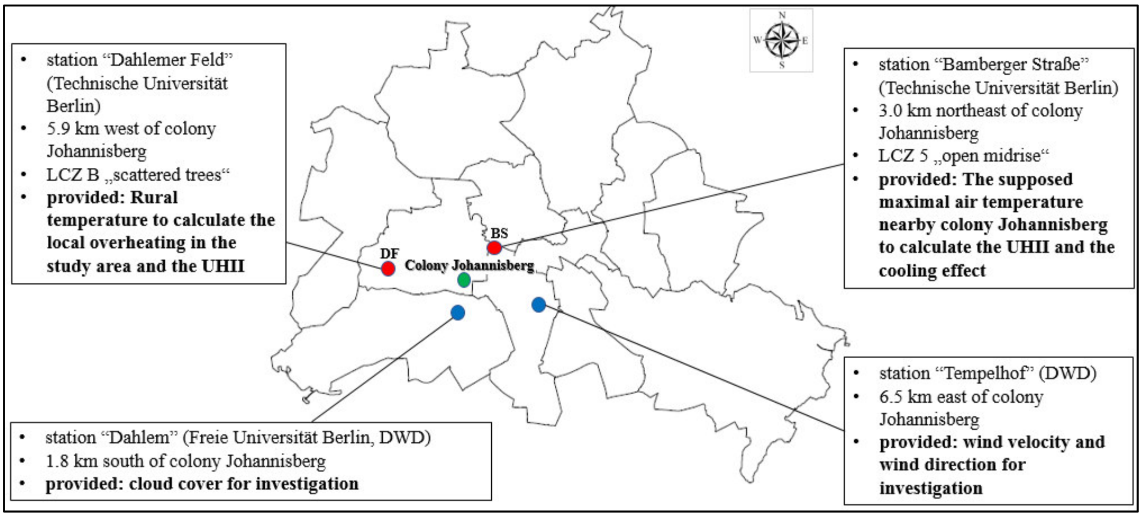


Fig. 18: Overview of the locations of additional used observational data with the colony Johannisberg (green), the two stations of the Technische Universität (red) and the two stations used to include relevant weather observation by the Climate Data centre of the DWD (blue).

6.5 Data analysis

The data of this work were obtained from various sources and first had to be checked. To analyse the data, the R programming language was used by the user interface R-Studio version 3.4. All measured data were controlled for outliers and missing values, which were set to NA (not available values). Outliers were defined as temperature values outside a range between 5 and 35°C which were not reached during the measurement period with exception of sporadic failure values at sensor DK 211. From these temperature values a main part could be corrected with older measurements so that in total 63 NA values from over 45000 minute-values resulted. Additionally, in general temperature changes above 2 K within 1 minute were classified as outliers.

For the comparability of the measurements, the nine sensors for the measurement of the air temperature were calibrated by the Department of Climatology and the resulting gain and offset values were included in the measured data (cf. section 6.2.2). After checking for error values and data gaps, the measured data of the fixed sensors were converted to hourly averages per aggregation of the minute values to the concerning hour. As a result, the values were no longer subject to spontaneous fluctuations and, on the other hand, were more meaningful and better comparable. The data from the HuMVe were included in the study as minute values. All the results of this work are presented in central European time (CET) to make them better comparable to other works. Subsequently, all data, measured by fixed sensors, were brought to a consistent time-period. This included every 32 nights between 31/05/2017 and 02/07/2017. Nights were defined as the period in which no direct solar radiation hit the entire study area. Due to the season of maximum sunshine duration, the night period was short and included the hourly averages between 20 CET and 03 CET, corresponding to the total period from 20:01 CET to 03:59 CET. This period is based on the latest sunset (20:33 CET) and earliest sunrise (03:42 CET) in June 2017 in Berlin and should ensure that the measurements were not influenced by direct sun radiation. On-site observations confirm that the sensors were not exposed to direct sunlight in this time-period.

6.6 Used parameters

Since this work investigated the cooling effect of the allotment colony Johannisberg, different temperature differences (ΔT) are used for the investigation, with the most relevant being briefly presented below. An important parameter was the regional difference in air temperature between the fixed sensors in the investigation area (T_i) and the air temperature at Dahlemer Feld (DF) (T_{DF}), representing the local nightly overheating in comparison to the rural surroundings of Berlin:

$$\Delta T_{i-DF} = T_i - T_{DF} \quad (11)$$

Since the station Bamberger Straße (BS) is assumed to represent the maximal possible nightly air temperature in the investigation area and therewith also in the southwestern part of city, the difference in air temperature between the stations BS (T_{BS}) and DF (T_{DF}) represents the UHI intensity in this work:

$$UHII = \Delta T_{BS-DF} = T_{BS} - T_{DF} \quad (12)$$

In order to assess the cooling effect by the colony Johannisberg on its adjacent urban neighbourhood, the difference of air temperature between the station BS T_{BS} and the sensors in the air temperature measured at the sensors in the investigation area T_i should give a good estimate for the maximal $cooling\ effect$, respectively the maximal possible temperature or UHI reduction by the colony Johannisberg:

$$cooling\ effect\ = \Delta T_{BS-i} = T_{BS} - T_i \quad (13)$$

Also the temperature differences between the regarded allotment area and its adjacent urban neighbourhood are important for the investigation. However, the in section 4.3 presented PCI should not be used in the following. Allotment gardens as subject of this work have a specific surface characteristic. This differs significantly from the urban parks mainly by the buildings such as arbours and sheds, the partial compaction of the soil (Horbert, 2000) and the spatial limitation of each allotment garden. The deviations of gardens and parks also affect the use and the UES (Speak et al., 2015). Allotment garden colonies also differ from areas with single-family houses due to the small size of the arbours and the development of gardens that are for example comparative rich in fruit trees and vegetables (Der Senator für Stadtentwicklung und Umweltschutz, 1985) also because of the BKleingG (BDG, 2017). Furthermore, exists up to now no suitable LCZ for allotment gardens. Allotment gardens as a kind of private urban land use should represent a transition-form between the local climate zones LCZ 6 "open lowrise" and LCZ B "scattered trees" (cf. Stewart and Oke, 2012). However, the cooling effect of allotments has so far not been quantified with any specific size. Because no park was studied in this work, the study area should not be confused with a park and there is still no adequate term for the temperature difference between allotment garden areas and their surrounding area, in the following the "Allotment Cool Island" (ACI) is introduced. The ACI intensity (ACII) is thereby the difference between the maximum air temperature of the adjacent urban environment of the colony (T_u) and the minimal air temperature inside the colony (T_c):

$$ACII = \varDelta T_{u-c} = T_u - T_c \quad (14)$$

Because the relevant cooling effect for the urban residents starts in the region of the colony border area from which on the landcover changes from allotment gardens to typical urban built-up area, the temperature differences between the colony border and the built-up area are especially important (cf. hypothesis in chapter 2). Thus, an important temperature difference is that between the air temperature outside of the colony border (T_i) and the air temperature in the area of the concerning colony border (T_{cb}) (10), since this is the part of the ACI which is efficient outside of the colony borders and therewith an "effective ACI intensity". Despite of the importance of this temperature difference, it is rather seldom contemplated but used for example in some works which investigated the extend of the cooling effect (Farny and Kleinlosen, 1986;

Upmanis et al., 1998). However, in this work this temperature difference (15) plays a key role to quantify the benefit of the allotment garden colony Johannisberg on its adjacent urban neighbourhood.

$$\Delta T_{i-cb} = T_i - T_{cb} \ (15)$$

To get a better understanding of the many used indices in this work, Fig. 19 gives a schematic overview over the corresponding locations in the investigation area:

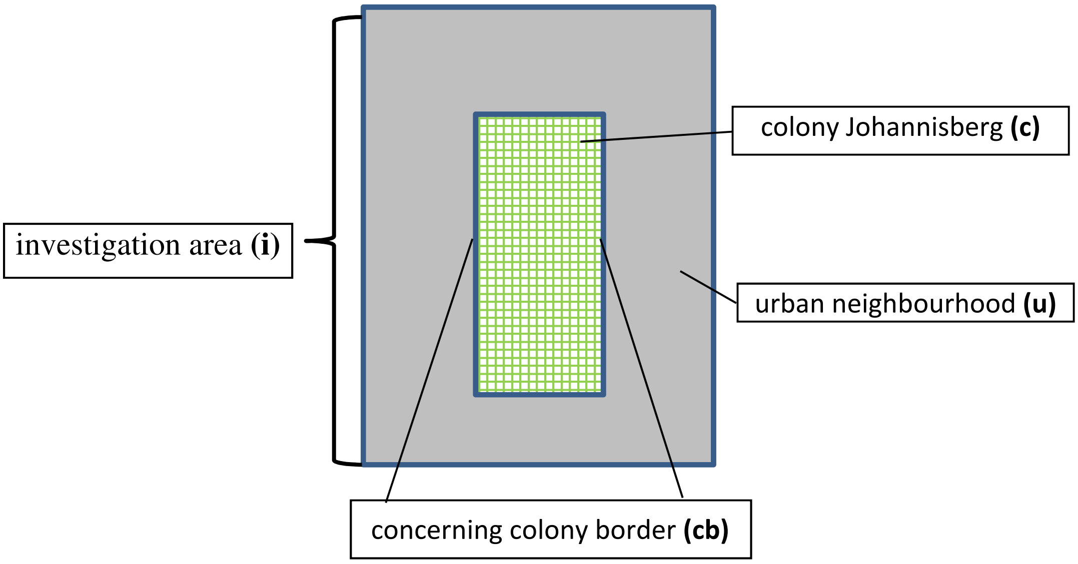


Fig. 19: Overview of the used indices for the parameters in the investigation area.

7 Results

The following result section in divided into four parts. After a short overview over the weather-conditions during the investigation period, follows a first general overview over the measured ACII and the UHII. Subsequently follows a more exact spatial analyse of the local temperature differences in the study area. This is divided into three parts: Firstly, the study of all nights of the investigation period, secondly the investigation of radiation nights and thirdly the findings concerning the influence of the superordinated wind. The section closes with the results of the mobile measurements.

7.1 Weather conditions during the investigation period

Overall, the weather conditions during the investigation period were satisfactory for the implementation of the study. The study began with the ending of a longer period with dry weather conditions with much sun radiation and adequate, a view days before the field measurements also obvious above average air temperatures. Afterwards, a period of changing weather conditions followed with short periods with radiation weather conditions. A longer radiation-rich and dry weather-period occurred from June 18 to June 21 (cf. Fig. 20). This was furthermore the period with the highest maximum temperatures in the study area. Although the following time-span of the investigation period was dominated by cloud-rich and occasionally wet weather conditions, the investigation period was in total sufficient to investigate the cooling effect of the colony Johannisberg. To get a better imagination, Fig. 20 gives an overview about the relevant weather parameters during the investigation period.

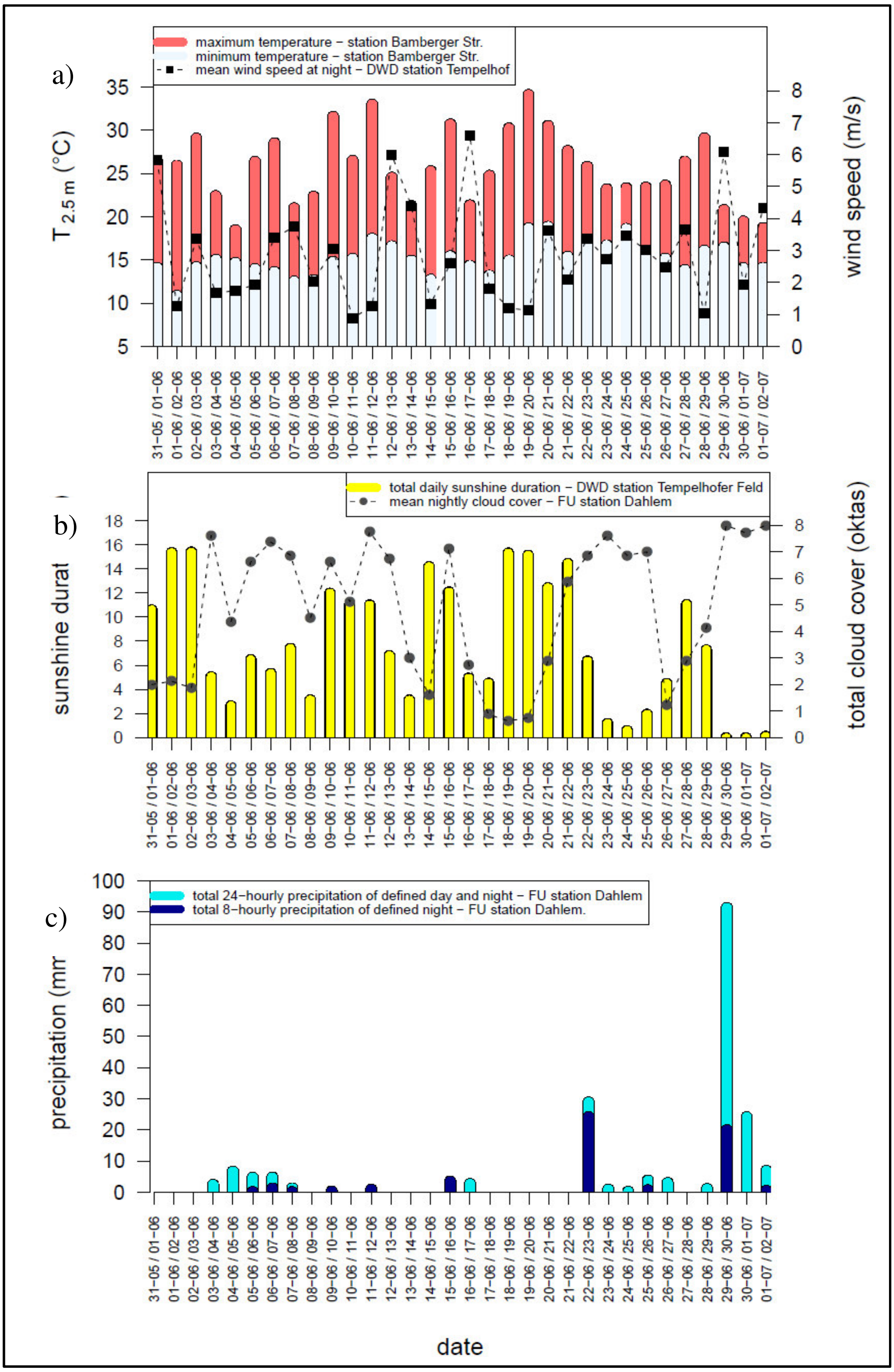


Fig. 20: Weather conditions during the investigation period: a) Maximum air temperature at BS during the defined day periods (04:00–19:59 CET) and the minimum temperature of the following night periods (20:00–03:59 CET). b) Total sunshine duration of the defined day and the mean cloud cover of the following defined night. c) Total precipitation amount of the defined night and the defined day and night together. Data Sources: Stadtklima-Messnetz Berlin (TU Berlin), Climate Data Centre (DWD), 2017.

7.2 General overview over the ACII, the mean local nightly overheating in the investigation area and the UHII at Bamberger Straße

One of the main motivational points for this work is the UHI of large cities, which can significantly increase the thermal stress at night in cities of mid-latitudes such as Berlin (Fenner et al., 2014; Scherer et al., 2014) (cf. chapter 1). To determine how strong the UHI can be in the studied southwestern centre area of Berlin during the investigation period, the UHI intensity was calculated as the difference of the urban reference stations "Bamberger Straße" and the rural reference station "Dahlemer Feld" (cf. section 6.6). This was also assumed to be the maximum possible UHI in the environment of the colony. For the entire measurement period, the mean UHI intensity is 1.4 K with an absolute minimum of -3.2 K (June 22 to 12:00 CET) and an absolute maximum of +10.3 K (June 2 to 02:00 CET). Fig. 21 shows that there existed consistently positive UHI intensities for the nights, while negative UHI values are noticeable during the day, but with much lower values. On ten days and therewith almost one-third of the almost 32-day-lasting series of measurements, positive UHI intensities of more than 6 K were achieved. Thus, a remarkable nightly overheating in the inner urban area of Berlin in comparison with the rural environment was not uncommon during the investigation period. In this context it makes sense to compare the urban overheating with the colony-induced cooling summarised in the ACII (Fig. 22) described in section 6.6. The average value of the ACII over the entire study period was 0.8 K. Fig. 22 shows obviously short-term outliers of more than 4 K (absolute maximum 4.6 K). Those deviating values resulted every time in the morning between 7 and 8 CET, when sensor East_80m was direct irradiated by the sun while the reference sensor in the colony EAST_CB was still in the shade of the adjacent houses. Nevertheless, when only the values of the defined night-period are considered, the maximum ACI reached 3.2 K at June 2 between 3 and 4 CET between the sensor West_160m, roughly 160 m western of the colony and the sensor CC in the colony centre.

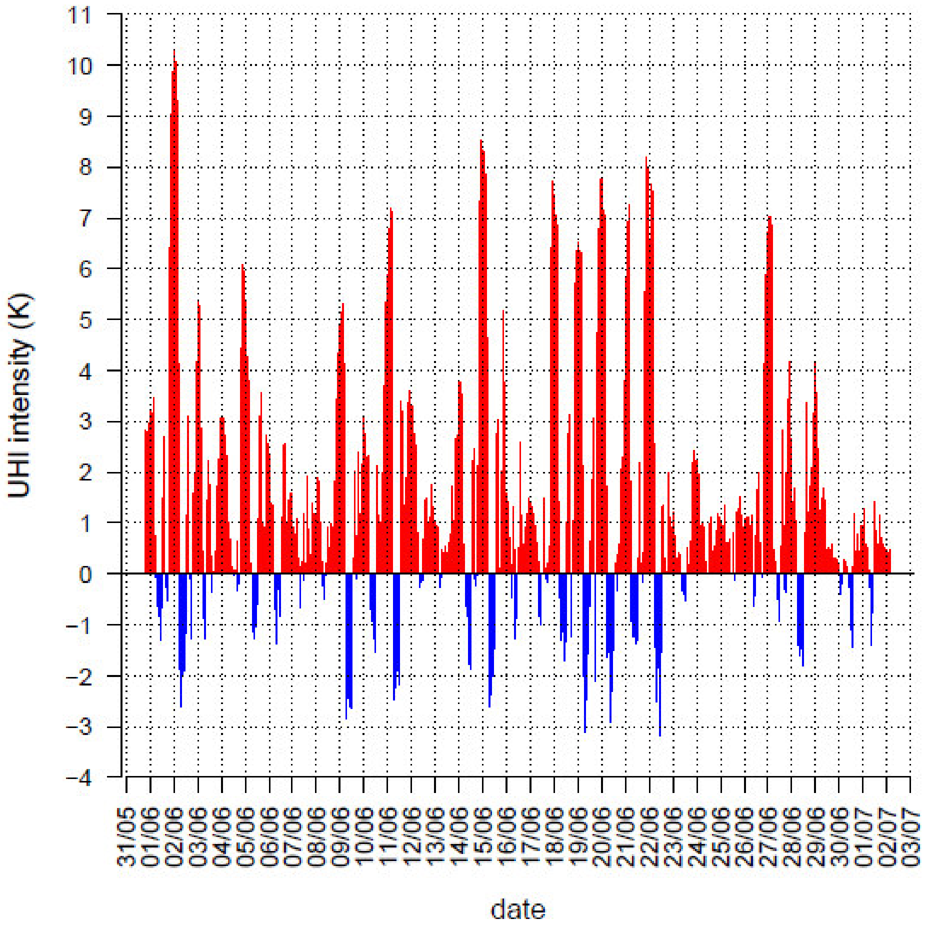


Fig. 21: UHI intensity between the stations BS and DF for the whole investigation period. Data basis: Hourly averages of air temperature.

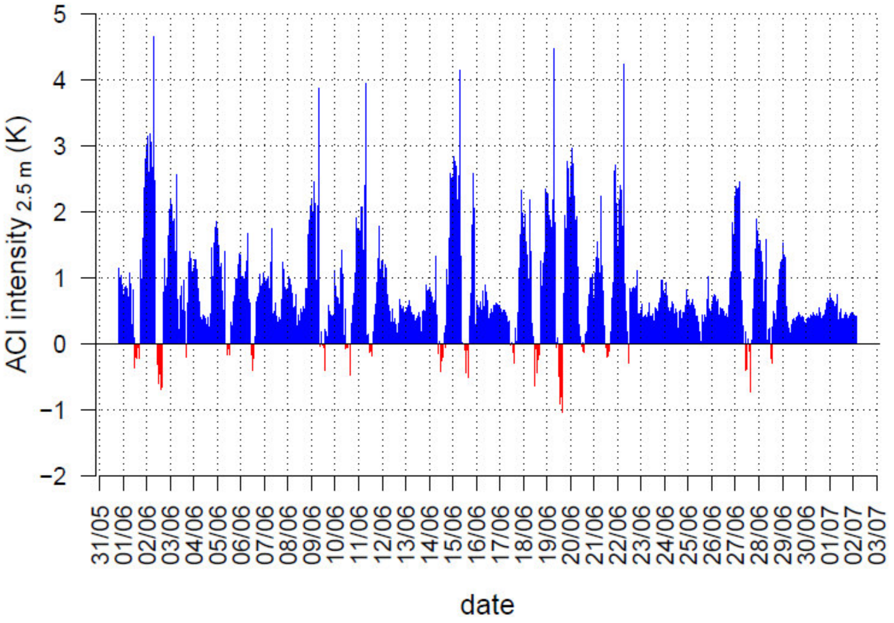


Fig. 22: ACI intensity between colony Johannisberg and its adjacent urban neighbourhood for the whole investigation area. Data basis: Hourly averages of air temperature.

During the day the ACI intensity shows partially negative values, stating, that it was also warmer at the coolest measurement point inside the colony than at the warmest reference measurement point in the built-up neighbourhood. The highest negative deviation was reached on June 19 to 17 CET with -1.1 K. At that time, the lowest air temperature measured in the colony centre was 31.1 °C and the highest temperature in the built-up area outside the colony was 30.0 °C at sensor EAST_80m. This day was at the same time the only hot day in the investigation area with maximum temperatures above 30 °C.

However, by concentration on the night hours from 20 to 03 CET as subject of this work the ACI intensity shows clearly positive values, whereby the ACI reached in 10 nights intensities of more than 2 K (Fig. 23). The highest measured nocturnal temperature difference was reached during the night from June 1 to June 2 with 3.2 K.

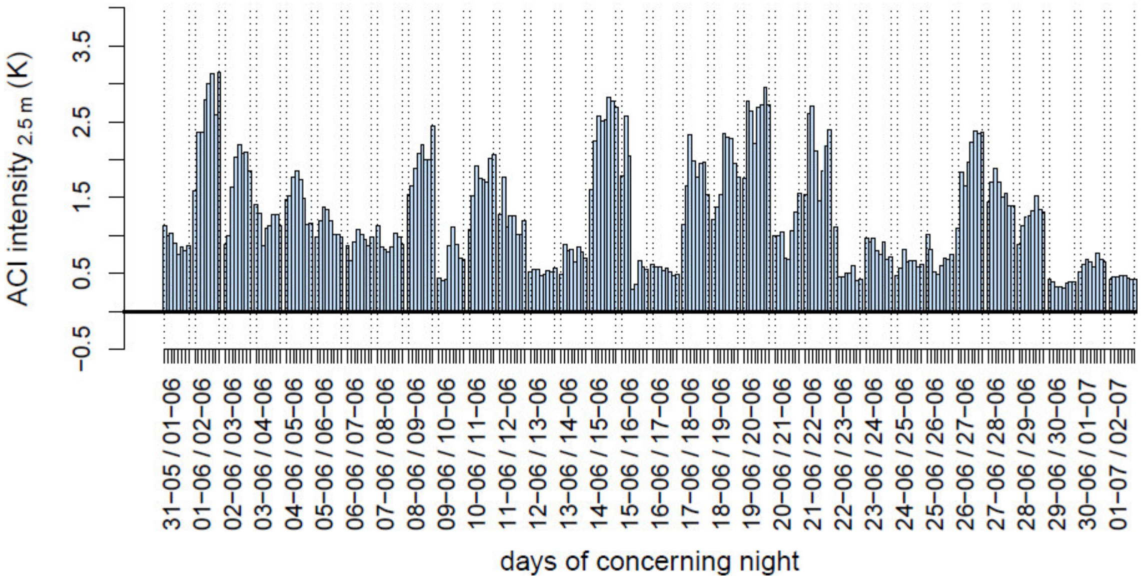


Fig. 23: ACI intensity of the colony Johannisberg for the defined nights in the investigation period. Data basis: Hourly averages of air temperature.

Already these results indicate that the colony Johannisberg is during night an obvious, occasionally remarkable cool island in the Berlin district Wilmersdorf. However, to assess the positive effect of the ACI on the built environment, it is necessary to concentrate on the air temperature differences between the colony border areas and the adjacent urban neighbourhood. In this work, this difference in air temperature is described by ΔT_{i-cb} as efficient part of the ACI that interacts with the urban environment (cf. section 6.6).

To get a first overview about the mean temporal progress of this parameter, the mean daily course of ΔT_{i-DF} is shown in Fig. 24 together with the local overheating of the investigation area caused by the urban heat island, quantified as ΔT_{i-DF}. It is noticeable that the temperature difference of sensor EAST_CB to the station DF (ΔT_{East_CB-DF}) and therewith the local urban heat island effect is from 12 to 16 CET only a short time above those of East_80m and East_160m. Another conspicuous feature is that ΔT_{East_80m-DF} increases again to 7 CET, while at the same time that of ΔT_{East_CB-DF} decreases (Fig. 24). At night, $\Delta T_{East\_160m-DF}$ is on average surprisingly lower than ΔT_{East_80m-DF}. These peculiarities are correspondingly also evident in the case of the temperature differences between colony border and built-up neighbourhood ΔT_{i-cb}. At the western colony side at night, ΔT_{i-DF} is significantly less pronounced than in the built environment and the same applies even more for the eastern colony border (Fig. 24). The maximum difference is visible in Fig. 24 and was reached on both western sensors on average between 0 and 2 CET (0-CET and 1-CET mean values). During this time-period it was at WEST_80m in mean 0.7 K and at WEST_160m 0.8 K warmer than at WEST_CB. To the east of the colony, higher temperature differences occurred at the colony-closer sensor EAST_80m (78 m east of the colony border). Here the nocturnal temperature differences to the eastern colony border reach up to 1.1 K and are larger than to the west of the colony, whereby they were reached between 1 and 2 CET. Noticeable is also the strong positive peak of ΔT_{EAST_80m-cb} to 7 CET in the morning. The comparison with the progress of ΔT_{i-DF} in Fig. 24 illustrates thereby, that this peak is caused by the mentioned warming of sensor EAST_80m by sun radiation (cf. section 4.5) while the sensor of at the east colony border EAST_CB was still protected in shadow and hence still remarkable cooler than that at DF. To the farther sensor East_160m, the maximum temperature difference is 0.1 K lower. By day west of the colony, however, ΔT_{i-DF} -values are slightly higher at the western colony border than in the western adjacent built-up area of Homburger Straße with a maximum deviation of -0.5 K at sensor WEST_160m. In contrast, the eastern colony border is only at one time-step obvious warmer than both outer sensors EAST_80m and EAST_160m, namely to 16 CET, when sensor EAST_CB was in mean temporarily stronger radiated by the sun.

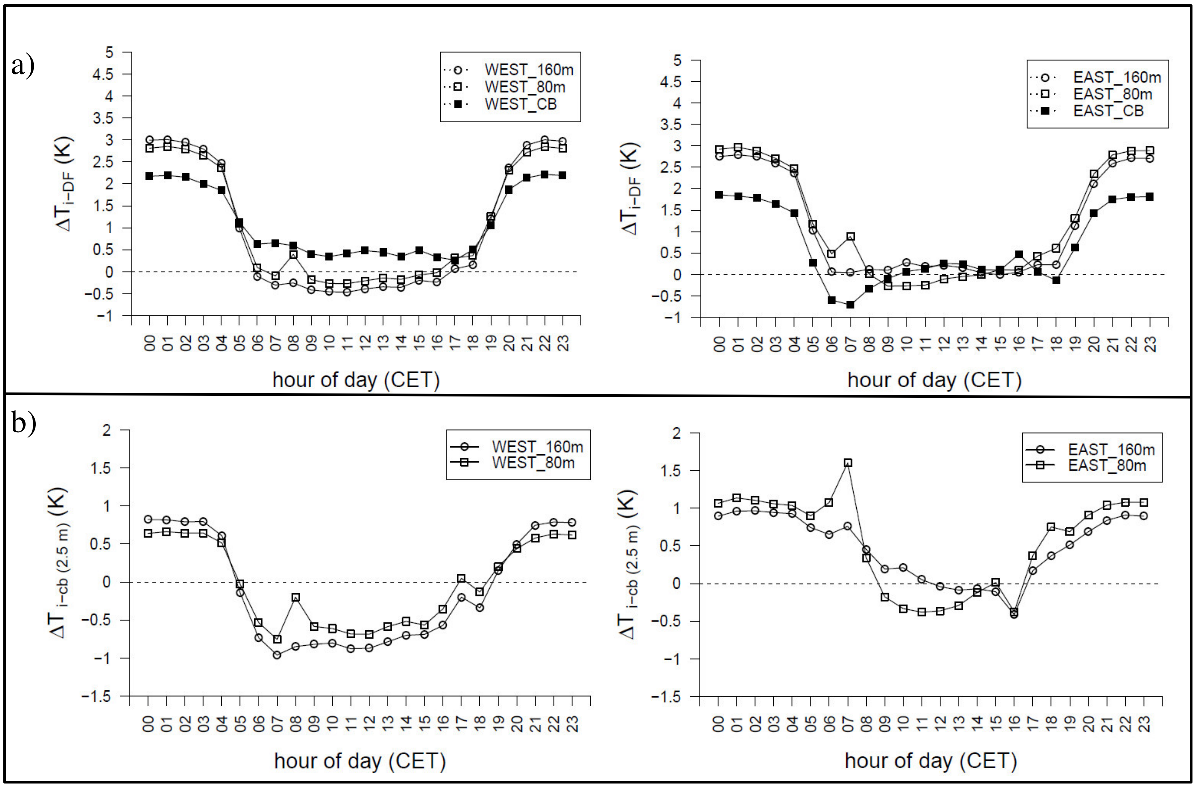


Fig. 24: Over the whole investigation period averaged 24-hourly course of: a) the local urban overheating in the investigation area ΔT_{i-DF} and b) ΔT_{i-cb} as part of the ACI which is efficient in the adjacent built-up area, respectively applied for the western part of the investigation area (left) and the eastern part of the investigation area (right).

7.3 Spatial analysis of the local temperature differences

7.3.1 All nights

In the following first the distribution of the different used parameters explained in section 6.6 along Homburger Straße should be presented on basis of all nightly hour values of the investigation period. This approach without data filtering has the disadvantage that the results can be low for example due to the presence of nights with high cloud coverage, much wind and rain events. The advantage, however, apart from getting an overview, is the high significance of the values, which at least consist of 256 hour-values (32 nights with a length of 8 hours). An overview of the results over all defined 32 nights along the Homburger Straße is shown in Table 5 and in Fig. 25.

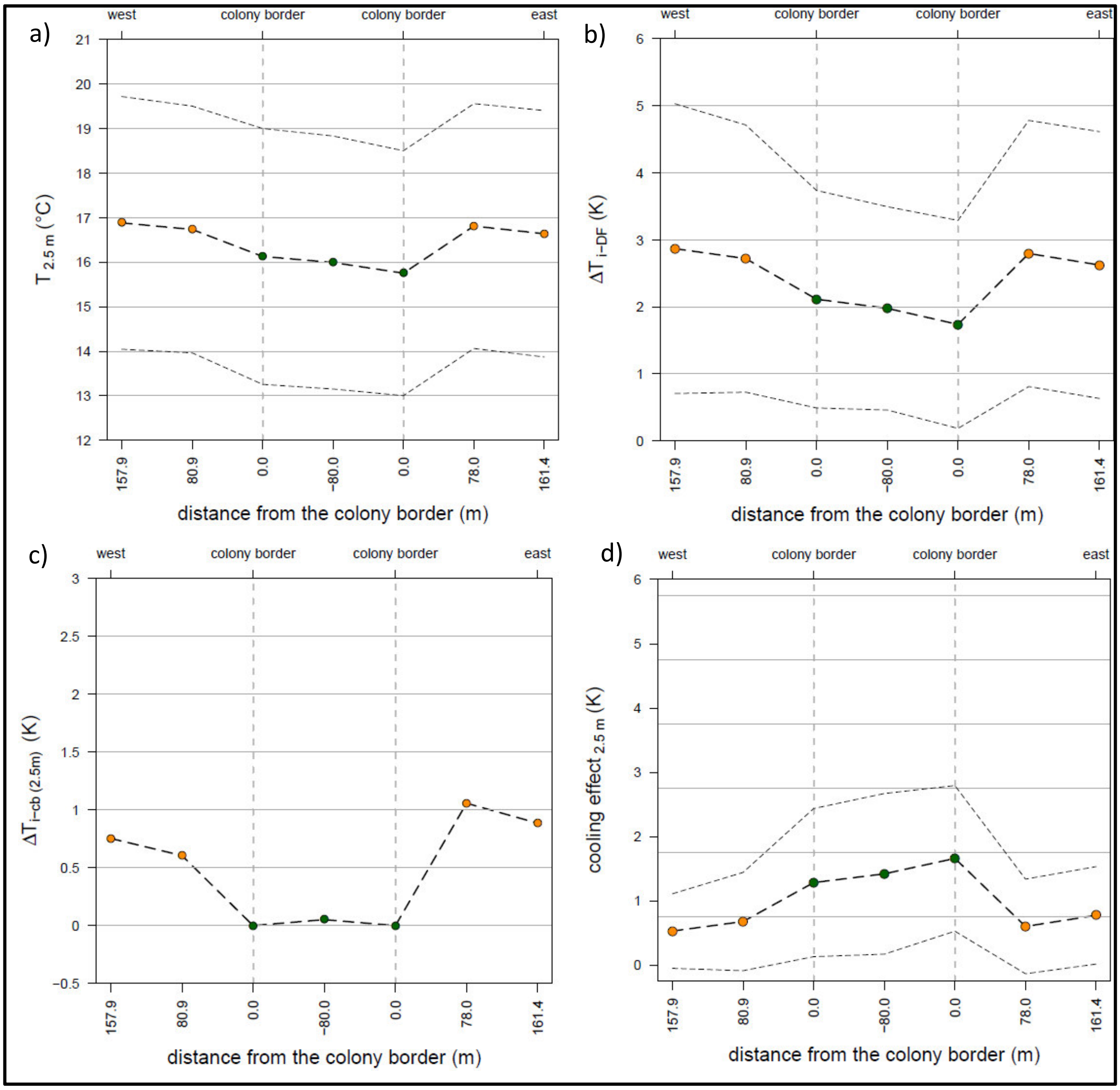


Fig. 25: Average values over the 32 nights of the measurement period along Homburger Straße of the air temperature (a)), the local urban overheating compared to the reference station DF (b)), the temperature difference between the measurement points and the concerning colony border (c)) and the cooling effect (d)). Green points: Values in colony, orange points: Values in the adjacent built-up area, dashed lines: Standard deviation.

Table 5: Results of Fig. 25

	WEST_160m	**WEST_80m**	**WEST_CB**	**CC**	**EAST_CB**	**EAST_80m**	**EAST_160m**
T (°C)	16.9	16.7	16.1	16.0	15.8	16.8	16.6
$\Delta \mathbf{T}_{\mathbf{i-DF}}$ (K)	2.9	2.7	2.1	2.0	1.7	2.8	2.6
$\Delta \mathbf{T}_{\mathbf{i-cb}}$ (K)	0.8	0.6	0.0	0.0	0.0	1.0	0.8
cooling effect (K)	0.5	0.7	1.3	1.4	1.7	0.6	0.8

The results of Fig. 25 show obvious that the air temperature within the colony is lower during the nights of the investigation period than in the built environment. The air temperature at the western colony border ΔT_{i-cb} is in mean over all nights 0.6 K higher at sensor W_80m and 0.8 K higher at sensor W_160m. Eastern of the colony ΔT_{i-cb} is even stronger with 1.1 K at E_80m and 0.9 K at E_160m (cf. Table 5). The local urban overheating in the investigation area in comparison to the rural area at station DF ΔT_{i-DF} is correspondingly lower in the colony than outside of it (Fig. 25). ΔT_{i-DF} is highest on average at sensor W_160m, 157.9 m west of the colony, with 2.9 K. In contrast, in mean it is lowest at the eastern colony border with 1.7 K. A correspondingly reversed pattern shows the estimated cooling effect. On average it is 0.5 K colder during night at sensor W_160m than at the reference station BS. At the eastern colony border the cooling effect is maximal with 1.7 K. The fact that the mean nightly air temperature is on average lower at sensor E_160m than at sensor E_80m is an indication that the cooling effect of the colony predominantly reaches only up to E_80m east of the colony. Western of the colony on the other hand, the expected trend is evident with a significant increase in temperature towards the residential area with a declining increase behind sensor W_80m. Against this background, it was considered how strongly the temperature difference between colony border and its built-up neighbourhood as efficient part of the ACI is related to the UHII of the southwestern part of the city. For this purpose, a linear regression analysis was carried out for all hourly mean values in the defined nights of the investigation period (Fig. 26):

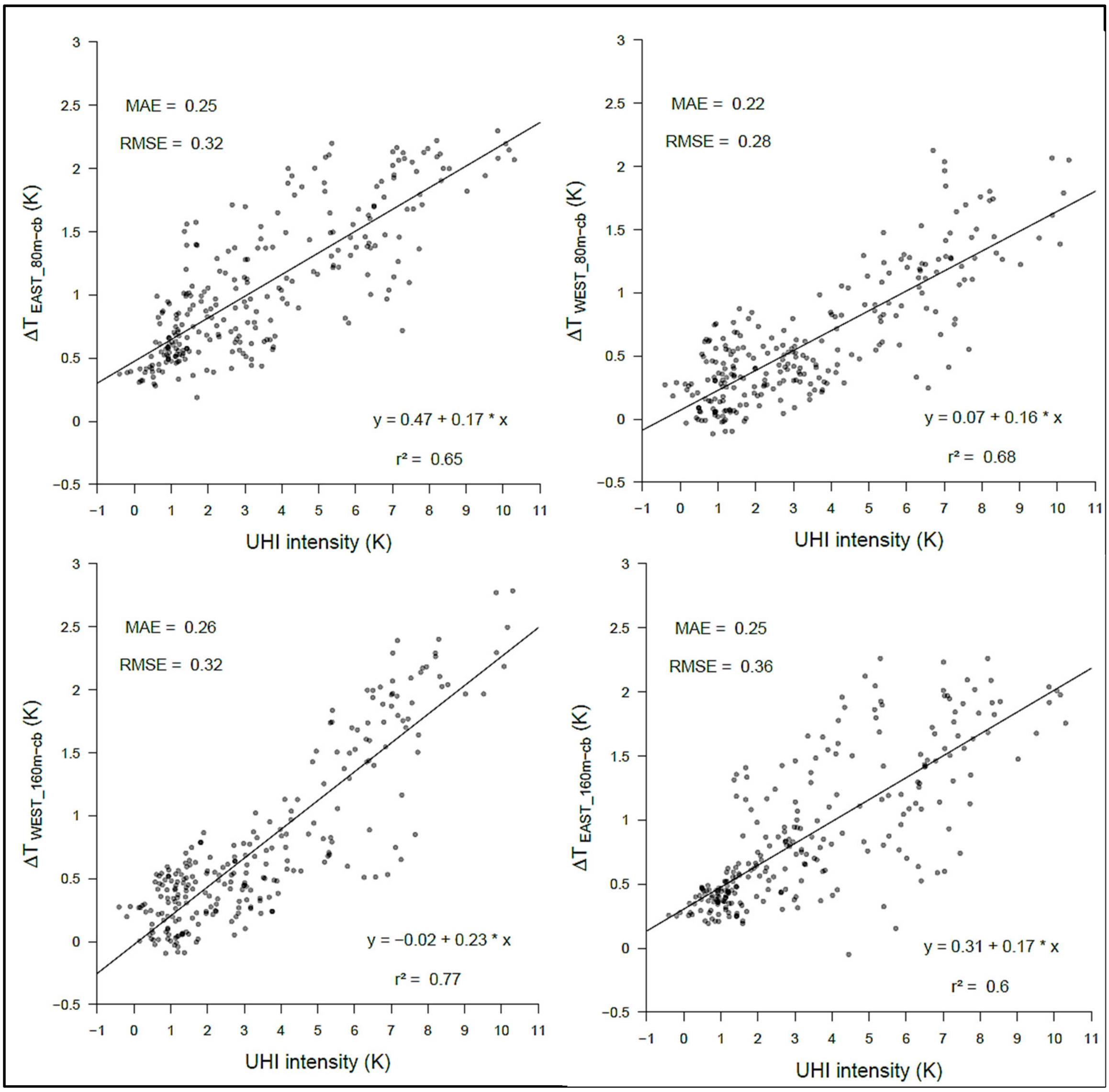


Fig. 26: Linear regression of the UHI intensity and ΔT_{i-cb} as the part of the ACI which efficient cools the urban neighbourhood, western (left) and eastern (right) of the colony.

Fig. 26 indicates a linear relation between the UHII and ΔT_{i-cb} which is also extremely high significant with a coefficient of determination $p < 0.001$ for all cases. The statistical correlation is thereby stronger in western of the colony where the coefficient of determination is also increasing with increasing distance of the temperature reference point from the colony border. However, Fig. 26 a)-d) show all a positive linear correlation with a slope of 0.16 to 0.23. This means that for a certain UHI intensity a temperature difference between built-up area and colony border of roughly 16 % of the UHII can be expected between WEST_80m and WEST_CB and roughly 23 % of it between WEST_160m and WEST_CB. But it must also be mentioned that Fig.26 indicates that for UHI intensities above 5 K, in trend rather higher values of ΔT_{i-cb} can be expected. The most important result is that the part of the ACI which affects the urban neighbourhood is most distinct in times of high UHI intensities and therewith then when it is most needed.

An even stronger linear correlation to the UHI intensity shows the ACI intensity itself, predicted to be in a dimension of a bit more than 25 % of the UHI intensity (Fig. 27):

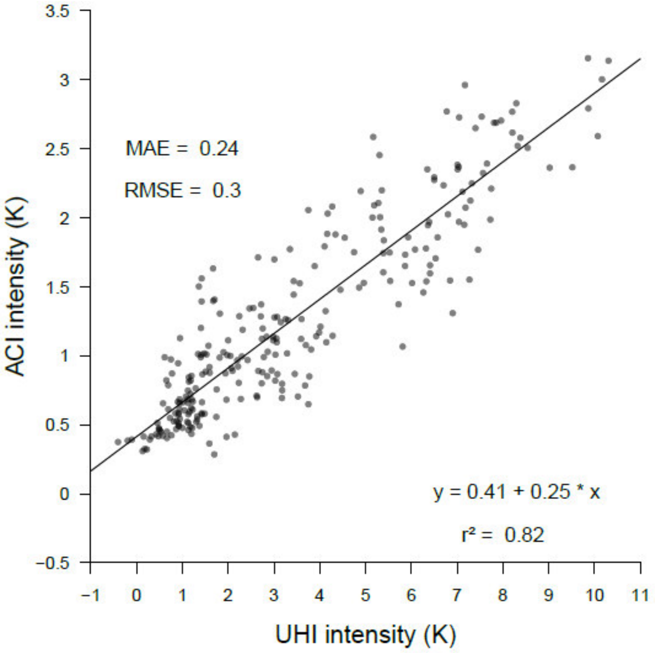


Fig. 27: Linear regression of the UHI intensity and the ACI intensity of the colony Johannisberg.

7.3.2 Radiation nights

According to literature, the PCI of a green area is particularly strong during windless and clear nights (cf. sections 4.3, 4.5). Thus, after all nights have been regarded together, the focus should be set on radiation nights with preferably autochthone weather conditions. Therefore, the data was filtered by using the measured wind speed at the station Berlin Tempelhof and the observed cloud cover of the station Berlin Dahlem. The filtering-process of the data was oriented on the work of von Stülpnagel, 1987 who set limits of 2 m/s in wind speed and 4/8 in cloud coverage as nightly mean values to classify nights with small atmospherical exchange. However, to be assured to regard only nights with really little total cloud cover, the criterion for the mean total cloud cover was set to 2/8 instead of 4/8, since in the case of a mean value 4/8 also some hours could be completely covered with clouds. Therewith, a night was classified as a radiation night when the mean cloud cover was not above 2/8 and the average wind speed was below 2 m/s, respectively in mean between 20 and 03 CET. This resulted in 5 radiation nights within the investigation period (01./02.06., 14./15.06., 17./18.06, 18./19.06., 19./20.06.) which should together represent the average temperature distribution during a radiation night. In order to get an overview of the associated daily values, the corresponding daily values (01.06., 14.06., 17.06, 18.06., 19.06.) extending from 5 to 19 CET, are partially also included in the investigation, although focus is set clearly on the nights.

By regarding the 24-hour-cycles of radiation days (Fig. 28), it becomes obvious that they show more distinct differences between the colony and the built-up environment than the average values over all nights (Fig. 24, section 7.2). During the day, it is warmer, especially in the west of the colony than in the west adjacent urban neighbourhood (Fig. 28). The temperature difference is significantly reduced to the closer sensor WEST_80m to 8 CET (appropriate to the hourly mean of the span 08:00 and 08:59 CET). To 17 CET, the temperature differences between colony border to both external sensors are for a short time significantly smaller. During daytime, the highest negative air temperature deviations are to 12 CET, whereby it is in mean 1.3 K warmer at WEST_CB than at WEST_80m and 1.5 K warmer than at WEST_160m. At 20 CET, the conditions reverse, and it becomes significantly cooler at WEST_CB than at the sensors in the adjacent western built-up area, with the highest difference being reached to 1 CET. To this time step it was in mean over all radiation nights 1.5 K colder at the western border of the colony Johannisberg than at WEST_80m and even 2.3 K colder than at WEST_160m. Thereafter, the differences decline again slightly.

The temperature variation between the eastern colony border and the eastern adjacent development area is similar during the radiation days, but there are some additional characteristics. The strongly positive deviation from EAST_80m to EAST_CB to 8 CET has already been commented in section 7.2 and can be attributed to the influence of solar radiation on EAST_80m. Conversely, to 17 CET strongly negative deviations of ΔT_{i-cb} are observable for EAST_80m, which was probably caused by irradiation of sensor EAST_CB by the sun at this time. Nevertheless, the other daily values should be more meaningful than these outliers since they are similar over a longer time span. Thus, the maximum positive temperature deviation of EAST_CB to EAST_80m is to 12 CET with 1.2 K and to EAST_160m to 13 CET with 0.7 K. In contrast, there are clearly positive ΔT_{i-cb}-values at night: These reach their maximum to both sides, western and eastern of the colony within the time span 01:00-01:59 CET. To this time at EAST_CB it is 1.8 K colder than at EAST_80m and 1.6 K colder than at EAST_160m (Fig. 28).

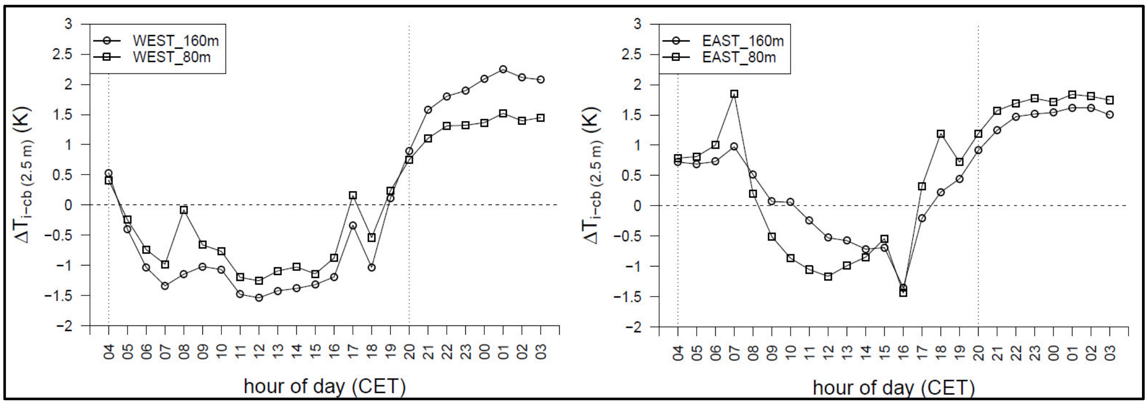


Fig. 28: Differences of air temperature between the western colony border and the adjacent residential area (left) and the eastern colony border and the adjacent residential area (right). The dashed vertical lines mark the borders between defined day and night.

For a better spatial overview over the parameters, the mean results of the seven fixed sensors along Homburger Straße are presented in Fig. 29. Thereby it becomes obvious that also in the temporal mean situation of the whole five considered radiation nights distinct differences in air temperature result between the border areas of the colony Johannisberg and the adjacent residential area. The western colony border is thereby in mean 1.3 K colder than the location at sensor WEST_80 m and even 1.8 K colder than at WEST_160m (Fig. 29). But also to the east exists on average a very strong temperature difference of 1.7 K to EAST_80m, to EAST_160m however, the difference declines again slightly to 1.5 K (Fig. 29). The course of air temperature indicates that there is in mean a continual increase in temperature west of the colony, decreasing with increasing distance to the colony. On the other hand, east of the colony, the temperature only increases up to the first sensor EAST_80 m and then decreases again, although slightly. A far-reaching cooling influence of the colony is thus present on average west of the colony in radiation nights, whereas to east the extension seems to reach only to the first sensor EAST_80m. The average temperature course in the radiation nights is also reflected in the ΔT_{i-DF} −values, standing for the local overheating due to the UHI phenomenon (Fig. 29). ΔT_{i-DF} at the western border of the colony is rounded on average 1.8 K lower than that 157.9 m further west. In the east the difference of ΔT_{i-DF} between EAST_CB and EAST_80m is with 1.6 K nearly of the same dimension. Even higher are the temperature differences of the investigation area to the station BS, leading to a minimum mean cooling effect over all radiation nights of 1.3 K at sensor WEST_160m and 3.5 K at sensor CC in the central area of the colony Johannisberg, where it is in mean 0.2 K colder than on average to the western and eastern colony border. Nevertheless, the distribution of air temperature shows that the eastern colony border area is colder than the western border area and is in mean less than 0.1 K warmer than the colony centre area at sensor CC (Fig. 29, a)).

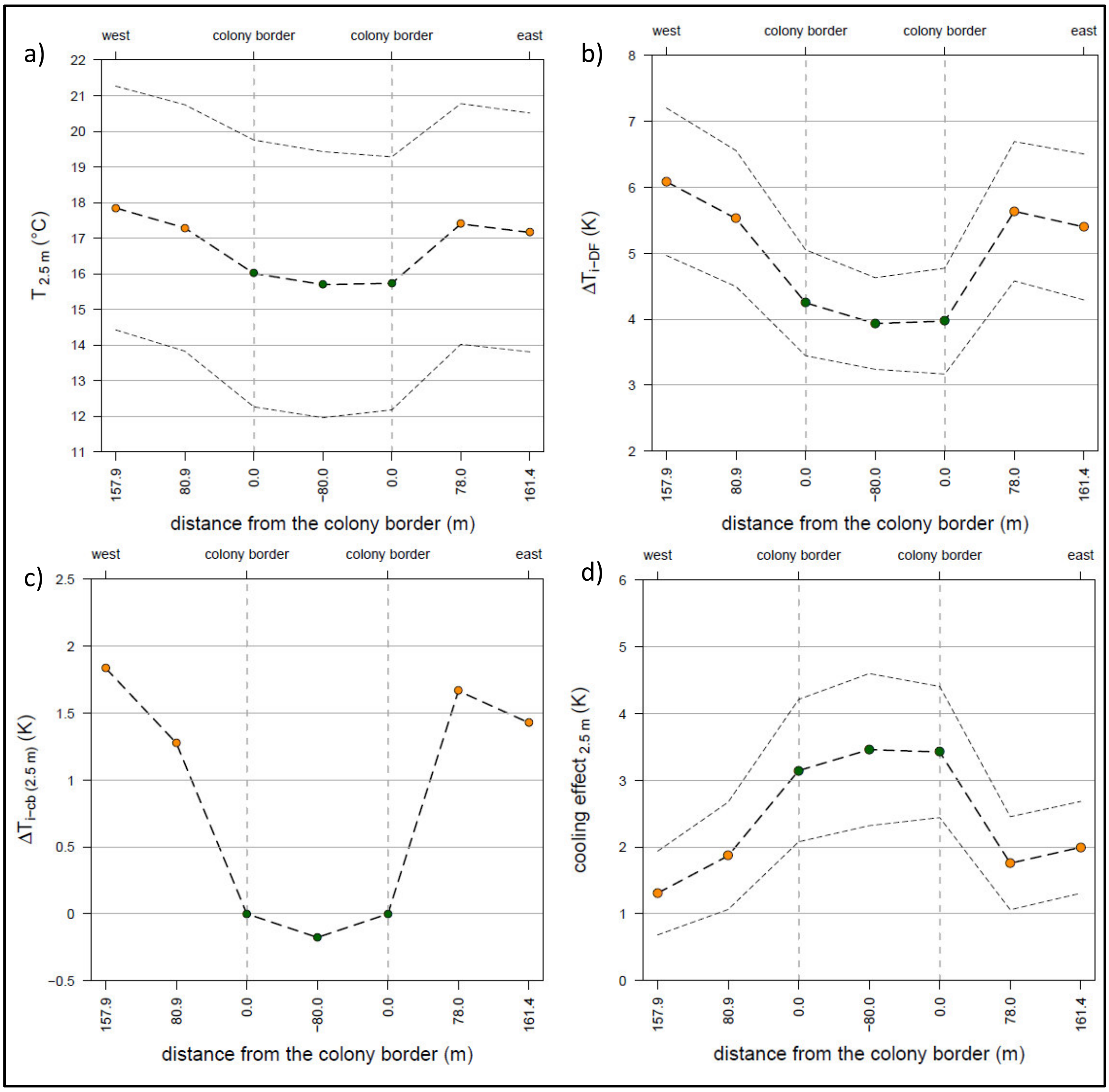


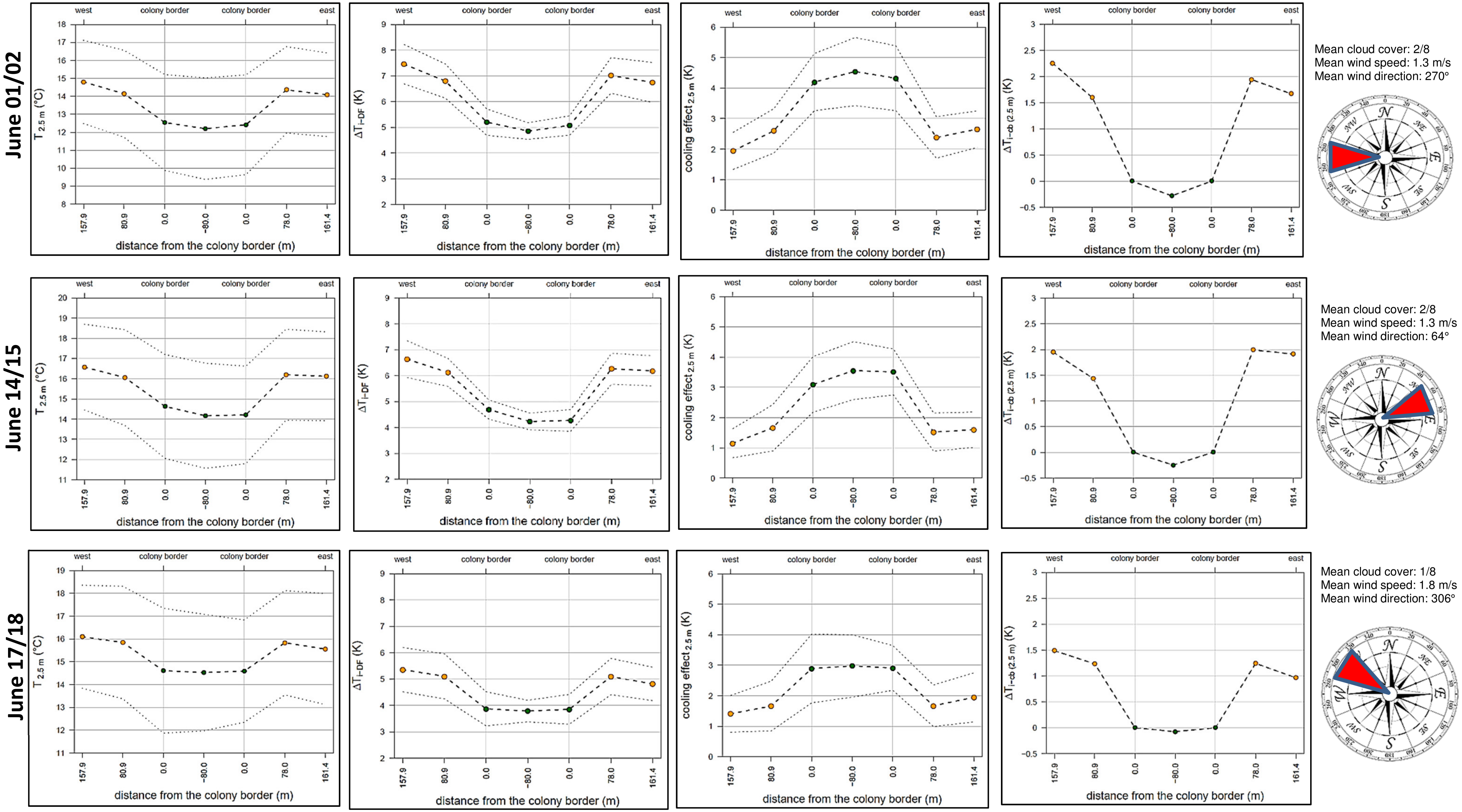
Fig. 29: Average values over the five defined radiation nights along Homburger Straße of the air temperature (a)), the local urban overheating compared to the reference station DF (b)), the temperature difference between the measurement points and the concerning colony border (c)) and the cooling effect (d)). Green points: Values in colony, orange points: Values in the adjacent built-up area, dashed lines: Standard deviation.

Thereby it must be mentioned that the results of Fig. 29 have a high and important expressiveness. Firstly, they represent nightly mean values, meaning that they can be temporally be obvious higher. Secondly, by these mean results over whole radiation nigths it becomes more obvious that the colony Johannisberg acts as an ACI, noticeable as remarkable depression of air temperature along Homburger Straße. Thirdly, the result in Fig. 29 indicate a cooling effect, extending western of the colony mostly further than to sensor WEST_80m in the radiation nights.

After the mean situation of the five radiation nights, the individual radiation nights shall be regarded (Fig. 30, Fig. 31) and compared with a situation, which did not fulfill the defined requirement for radiation nights (Fig. 31). Thereby it becomes obvious that in all radiation nights the colony Johannisberg was distinctive colder than its urban built-up neighbourhood. Furthermore, the air temperature, ΔT_{i-DF} for the quantification of the local urban overheating in comparison to the rural surroundings of Berlin, ΔT_{i-cb} and the cooling effect as temperature difference to BS show all a similar course during the five radiation nights. Important is that the temperature western of the colony increased in all nights with the distance to the western colony border, whereas eastern of the colony the air temperature declined again behind sensor EAST_80m in all cases. The wind direction alone had not much influence at these low wind velocities like a comparison of the night from June 14 to June 15 in Fig. 31 shows by comparison with the other four radiation nights, where the wind did not come from the east. At the night from June 17 to June 18 the lowest temperature differences occurred, probably due to higher wind speeds and the lower local overheating around the colony Johannisberg (cf. chapter 7.2, Fig. 20, a)). But also a lower radiation input during day seems to be reasonable, because below 5 sun hours occurred at June 17 during daytime (cf. Fig. 20, b)). However, it is obvious that the night with the highest UHI intensity from June 1 to June 2 also produced the highest temperature differences between the colony Johannisberg and its built-up environment. In this night the temperature was in mean at the western colony border 2.3 K below that at sensor WEST_160m and 1.6 K below that measured at sensor WEST_80m, reducing ΔT_{i-DF} from over 7.5 K at WEST_160m to values of 4.8 to 5.2 K in the colony area. Also important are the results for the night from June 19 to June 20 that show an interesting course of the temperature profile along the western part of the Homburger Straße with big temperature differences even behind the first western sensor WEST_80m, whereby the temperature differences between the sensors decrease only slowly with distance, namely 1.1 K from WEST_CB to

WEST_80m and 0.8 K from WEST_80m to WEST_160 m. With Bamberger Straße as reference station for the supposed maximal temperature in the urban neighbourhood of the colony Johannisberg, a nightly cooling effect mostly between 1 and 2 K can be assumed for the night from June 19 to June 20. Higher values occurred in the night from June 1 to June 2 with 1.9 K at WEST_160m, 2.6 K at WEST_80m and 2.4 K at EAST_80m and remarkable 4.6 K at sensor CC in the colony centre itself.

However, another picture occurred for a night, in which the UHI intensity was also considerable, but a wind velocity above 2 m/s and from norther instead western or eastern direction occurred. Together with the low mean cloud cover of 1/8, these deviations were enough to modify the temperature profile western of the colony. In contrast to all other situations, the cooling effect in the night from June 26 to June 27 did not reach the first sensor in the western built-up area WEST_80m. This can be seen in row 3 of Fig. 31, which shows that the mean nightly course of air temperature in the urban environment western of the colony was nearly constant, independently to the distance to the colony.



Mean cloud cover: 2/8
Mean wind speed: 1.3 m/s
Mean wind direction: 270°

Mean cloud cover: 2/8
Mean wind speed: 1.3 m/s
Mean wind direction: 64°

Mean cloud cover: 1/8
Mean wind speed: 1.8 m/s
Mean wind direction: 306°

Fig. 30: Average values over the first three defined radiation nights along Homburger Straße of: Air temperature, ΔT_{i-DF}, the cooling effect and ΔT_{i-cb}. Green points: Values in the colony area, orange points: Values in the adjacent built-up area, dashed lines: Standard deviation. Weather conditions are summarised on the right.

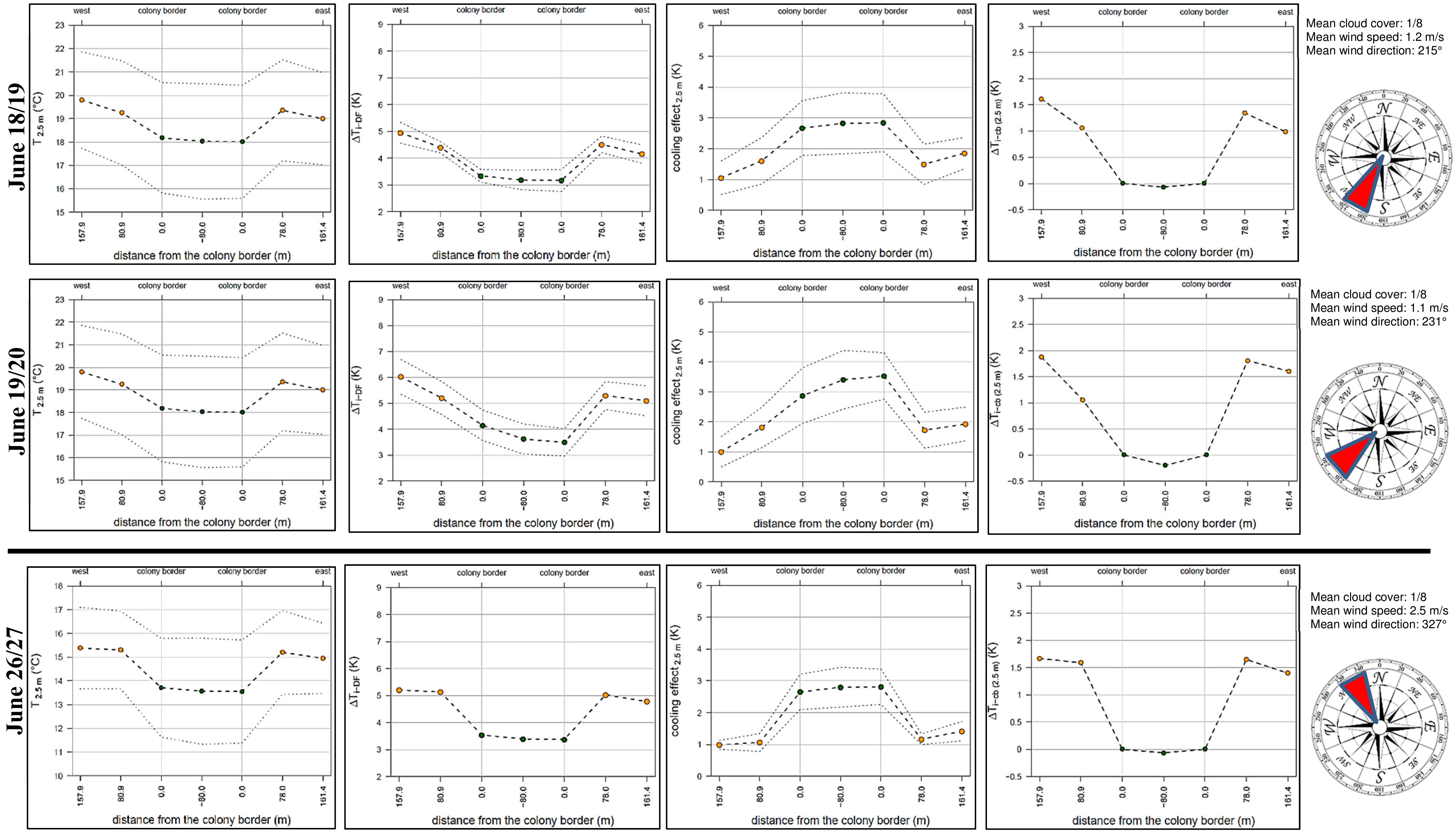


Fig. 31: Average values over the fourth and fifth defined radiation night along Homburger Straße and for the deviating night from June 26 to June 27 of: Air temperature, ΔT_{i-DF}, the cooling effect and ΔT_{i-cb}. Green points: Values in the colony area, orange points: Values in the adjacent built-up area, dashed lines: Standard deviation. Weather conditions are summarised on the right.

To complete this overview, the situation inside the colony Johannisberg during the nights shown in Fig. 30 and Fig. 31 shall be regarded for the six nights shown above.

In this situation all radiation nights show predominantly analogies concerning the distribution of air temperature with the highest air temperature at the station in the north (NORTH_CB) and mostly the lowest air temperature in the colony centre (CC) and the eastern border area (EAST_CB). However, in the night from June 17 to June 18 this temperature pattern deviated obvious, since then the lowest mean air temperature was measured in the centre and in the southern border area of the colony Johannisberg (sensor SOUTH_CB) (Fig. 32, d)). This indicates an advection of cold air from the colony parts northwestern of sensor SOUTH_CB. Reasons for the otherwise comparative high temperatures at SOUTH_CB are probably its exposed position between a descent of the colony area to the west and especially to the east. It is probable that a significant amount of cold air flows in these areas leading to higher air temperatures at SOUTH_CB as it would be in a smooth surrounding area. However, since the aim of this study was the investigation of the cooling effect especially on the urban neighbourhood the implemented position of SOUTH_CB is satisfying. Additionally, the high temperatures at SOUTH_CB in the nights from June 18 to June 19 and June 19 to June 20 (Fig. 32 d,e) are probably due to the advection of warm air from the adjacent built-up area southwestern of the colony. The on average noticeable low temperatures of sensor EAST_CB can be attributed to its protected position nearby a house which could lead to a reduction in air exchange with the urban environment. Secondly, EAST_CB was with 12.2 m distance to the Homburger Straße and 9.9 m distance to the eastern bordering fence of the colony relatively deep in the colony structure. The high air temperatures measured by NORTH_CB are probably due to a high and dense hedge which was nearly direct under the sensor. Hence the air exchange at this sensor was low, although it was the nearest of all to the colony border with a distance of 1.5 m. In the situation with higher wind speed from northern direction however, the pattern of Fig. 32, d) did surprisingly not occur, but therefore an extenuated form of the pattern of the other radiation nights. Reasons for this are difficult to find. Probably a mixing of urban warmer air from the UBL into the UCL due to turbulence effects could have lead here to high air temperatures. Additionally, higher air exchange processes inside the colony itself could have led to the weakened pattern of air temperature distribution compared to the most other radiation nights. A general overview over the pictured temperature values is shown in Table 6.

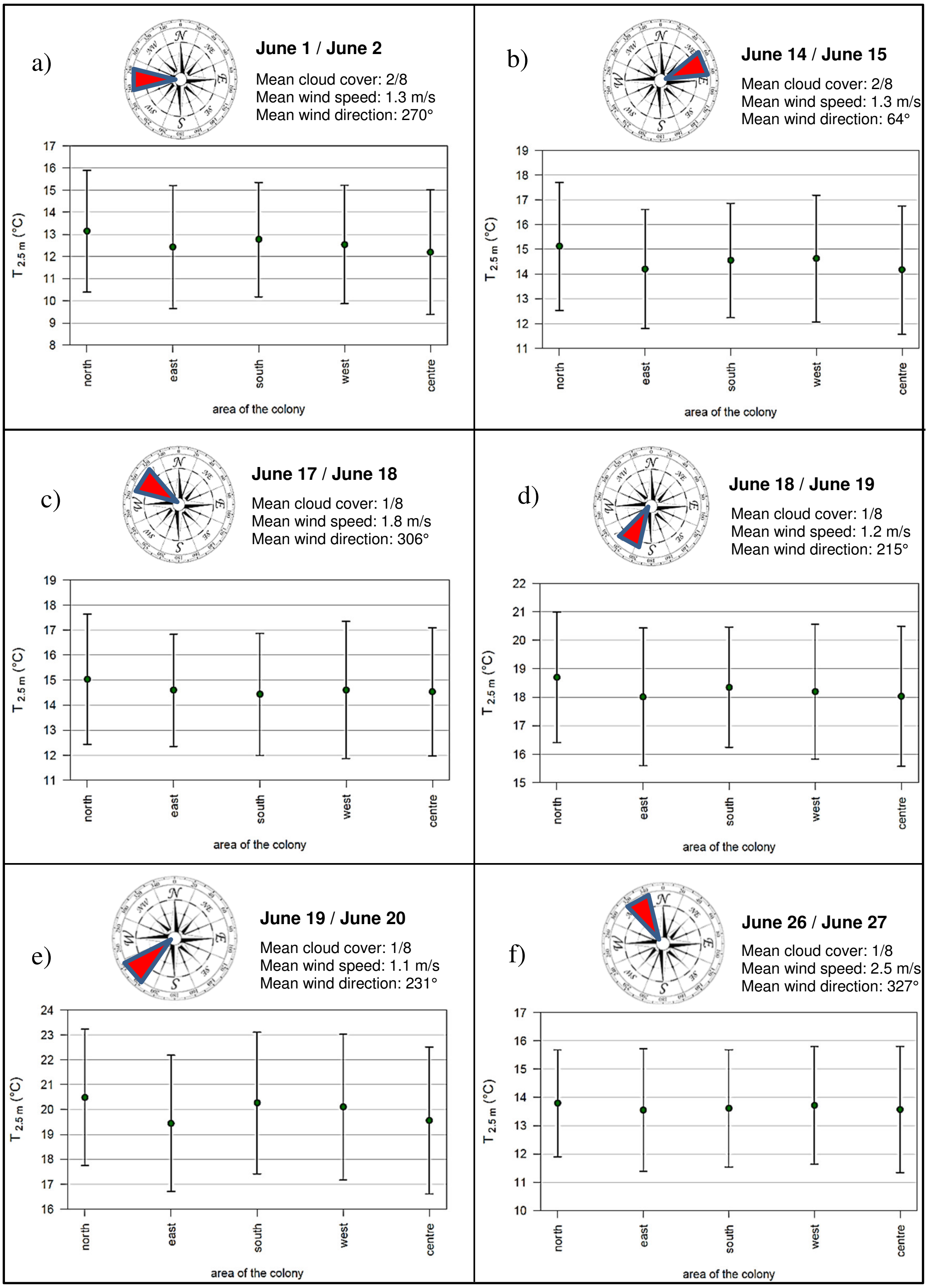


Fig. 32: Overview over the mean temperature distribution of the 5 radiation nights and the night from June 26 to June 27 with a mean wind speed of 2.5 m/s inside the colony Johannisberg. The error bars mark the standard deviation.

Table 6: Distribution of air temperature in the colony Johannisberg during five radiation nights and one night with northern wind and mean wind speed of 2.5 m/s

	North_CB	EAST_CB	SOUTH_CB	WEST_CB	CC
T in the night: 01./02.06.2017	13.1	12.4	12.8	12.5	12.2
T in the night: 14./15.06.2017	15.1	14.2	14.5	14.6	14.2
T in the night: 17./18.06.2017	15.0	14.6	14.4	14.6	14.5
T in the night: 18./19.06.2017	18.7	18.0	18.3	18.2	18.0
T in the night: 19./20.06.2017	20.5	19.4	20.3	20.1	19.6
T in the night: 26./27.06.2017	13.8	13.6	13.6	13.7	13.6

Fig. 29 showed already the mean temporal development of the air temperature differences to the concerning colony border. In this context the differences of two radiation nights to different time steps should be illustrated, respectively to the time steps when ΔT_{i-cb} is in mean over the radiation minimum and maximum developed.

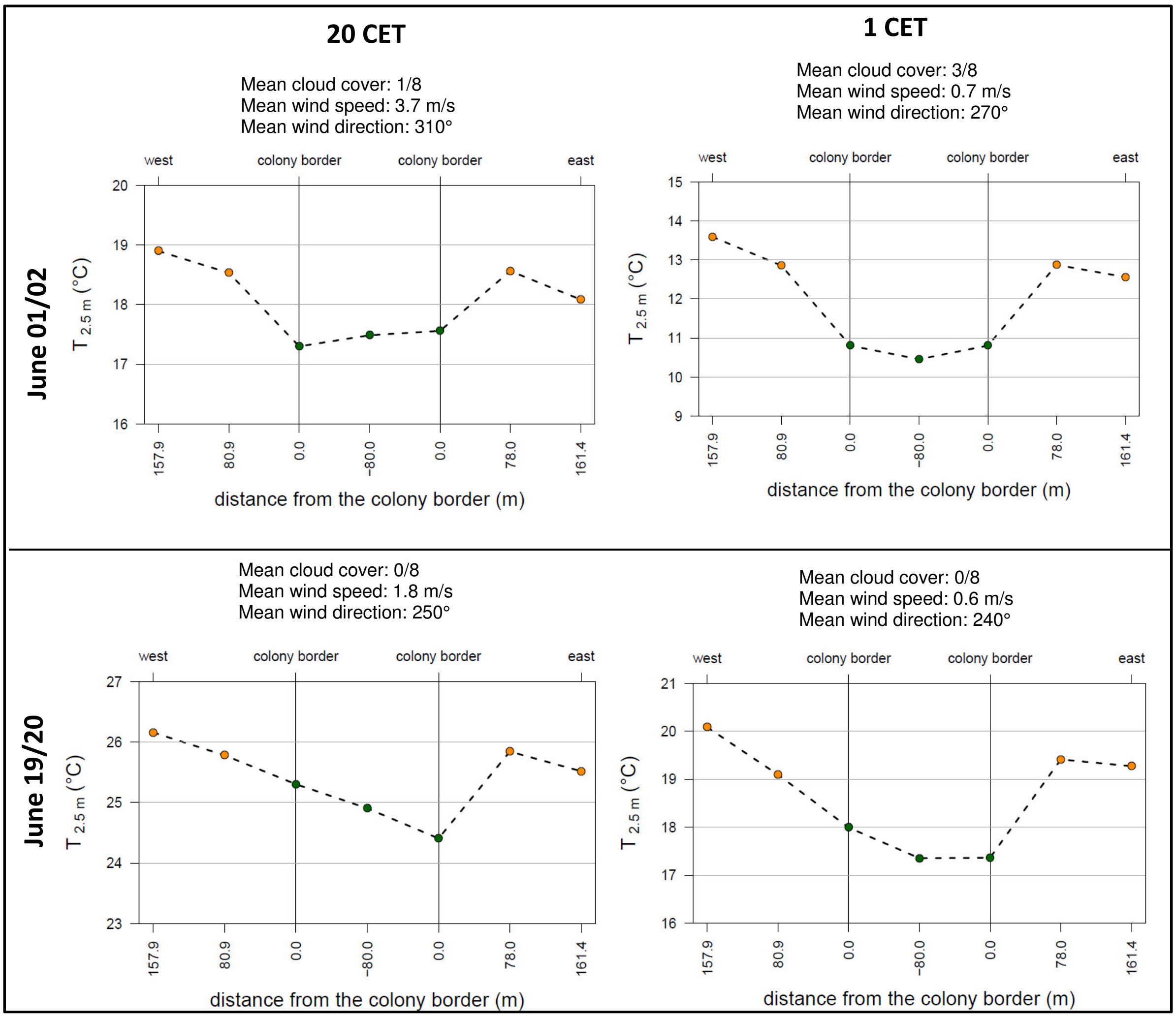


Fig. 33: Mean hourly temperature distribution along Homburger Straße to 20 CET (left) and 1 CET (right) during night for the two most pronounced radiation nights.

The results in Fig. 33 show that the temperature differences between the colony border and the urban environment remarkable develop during night, whereby the distribution of air temperature in the colony varies strongly. But also outside exist differences, especially western of the colony. In the night from June 1 to June 2 the air temperature mostly decreased between the western colony border and sensor WEST_80m, 80.9 m westerly of the colony with 2.1 K and by further 0.7 K between WEST_80m and WEST_160m, 157.9 m west of the colony Johannisberg to 1 CET. In contrast, the course in the same area was in the night from June 19 to June 20 nearly linear with a decrease of air temperature by 1.1 K between the western colony border and sensor WEST_80m and a further decrease by 1.0 K from WEST_80m to WEST_160m to 1 CET. In the night from June 19 to June 20 additionally existed an increase of air temperature by 0.7 K between the colony centre and sensor WEST_CB. Summarised the development of the ACI and its assumed interaction with the urban environment becomes clear with the comparison of the air temperature distribution through the colony Johannisberg along Homburger Straße by a comparison of the night periods to 20 and 1 CET. The night from June 1 to June 2 was that with the highest ACI intensity (3.2 K) and for the night from June 19 to June 20, additional mobile measurements were done. An influence of the weather conditions illustrated above on the temperature distribution outside of the colony cannot be specified, since the night with the better conditions (June 19 to June 20) had a lower ACI intensity. A solution can be that a strong interaction with the urban environment also lowers the ACII to a certain degree.

7.3.3 Influence of the superordinated wind

Fig. 32 already indicated an influence of the superordinated wind on the air temperature distribution inside and outside of the colony Johannisberg. To investigate the influence of the wind on the distribution of air temperature along Homburger Straße, the wind data of the DWD station Berlin Tempelhof were included in the investigation. The criteria for the data filtering were adopted by von Stülpnagel, 1987 with small change. For this part of investigation nights were selected in which the average cloud cover was below 4/8 and therewith a less strict criteria as for the radiation nights (cf. section 7.3.2). The hourly values of all nights were subdivided into moderately exchange situations (2 m/s <= mean wind speed <= 4 m/s) and high-exchange situations (4 m/s > mean wind speed <= 6 m/s), whereby the upper limit was set to 6 m/s on the basis of the literature research (cf. section 4.4). The wind was divided into the four main wind directions north (315–45 °), east (45–135 °), south (135–225 °) and west (225–315 °).

The large-scale 4 areas are used because the restrictions lead to an obvious reduction in data, despite of the proportionally long measurement period. For the investigation, first the approach of filtering by nightly mean values was implemented. Because of a lack of appropriate mean weather situations this approach leads only to a situation with northern and eastern wind under moderately exchange situations. Appropriately, the filtering process was done by hourly values in which the above criteria are met. Despite of the distance to the reference station for the wind, the advantage of this approach was that more different wind situations could be identified and that the shown wind direction was with high probability from the regarded directions, since the wind can also change its direction during night and the same is true for the cloud cover.

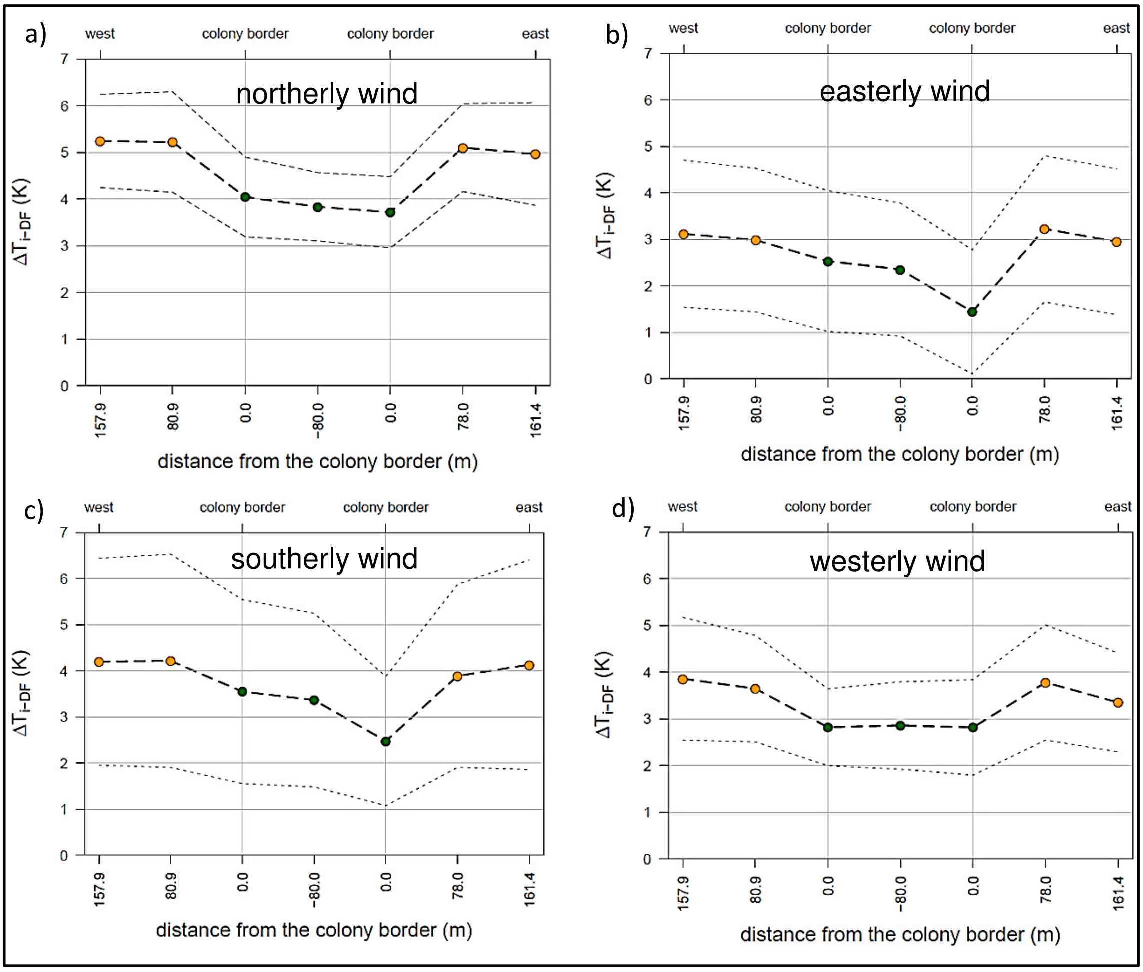


Fig. 34: Distribution of ΔT_{i-DF} of hourly measurement data with a mean wind speed of 2m/s–4 m/s and a mean cloud cover <=4/8 for different wind directions: Northern wind (a), eastern wind (b), southern wind (c) and western wind (d).

To assess the influence of the wind on the temperature distribution along the Homburger Straße, the distribution of ΔT_{i-DF} was considered. This approach has the advantage that not only the magnitude of the temperature differences along Homburger

Straße, but also the local acting UHI effect can be considered. For all nights with moderate atmospheric exchange (2 m/s <= mean wind velocity <= 4 m/s), a similar pattern was observed with visibly lower values of ΔT_{i-DF} inside the colony than in the built-up urban environment. The highest difference of ΔT_{i-DF} between the colony Johannisberg and residential area can be observed in situations with northern winds, where the temperature difference between the built-up area and the colony border reached 1.2 K between WEST_CB and WEST_80m and 1.4 K between EAST_CB and EAST_80m (Fig. 34). On the other hand, the temperature at the outermost sensors did not change with increasing distance obviously (Fig. 34). Thus, it can be stated that the superordinated wind can reduce the cooling effect along Homburger Straße remarkable, by a disturbance of the responsible ACI-advecting microscale wind system (cf. sections 7.3.2, 7.3.3), when it is strong enough and rectangular to it. Although the cooling effect is here reduced to maximum less than 80 m, an advection of cool air southern of the colony is probable but cannot be proven with the used measurement device. However, the described results have a high expressiveness since they base on the measurement data of two whole nights (June 20/21 and June 26/27).

The situation with a nearly constant temperature level western of the colony occurred also for situation with southern winds. In contrast, the assumed advection of cold air from the colony to the western and eastern adjacent urban neighbourhood could not be identified. An interesting pattern shows the situation with western winds, where an eastern transport of the cold air from the colony Johannisberg can be supposed. Instead, an a least noticeable temperature difference of 0.3 K occurred between WEST_160m and WEST_80m. Here the statement of von Stülpnagel that the microscale air circulation could also exist windward could have been occurred, whereby the western wind enforced the top wind of the microscale wind system due to consistent wind direction or did not much interact with it. An argument for both explanations is the existence of a high building rectangular to the course of Homburger Straße (Fig. 9, 11) at its western end. This high building structure could lead beside turbulence also to a wind shadow that hinders the superordinated wind to interact with the “tree-protected” air layer between treetop and ground along Homburger Straße west of the colony. In contrast, for situations with eastern wind, the colony around sensor EAST_CB seemed to be in a wind shadow of the adjacent buildings, respectively in an area, where warm wind air of the urban neighbourhood flows above the colony. In contrast, the more western colony parts had obvious higher air temperatures during periods with western wind (Fig. 34, b)). It can be supposed that during eastern wind situations the wind protected eastern part of the colony can cool down nearly undisturbed while the western areas of the colony become warmed by turbulent mixing with warmer air from the urban neighbourhood. Different results are obtained by considering night hours which show wind speeds of 4 m/s – 6 m/s. These results nevertheless base on less hourly values and showed air temperature differences between the colony and the adjacent built-up area of maximal 0.2 to 0.6 K and only 0.1 to 0.2 K between the two respective outer sensors.

7.4 Mobile Measurements

7.4.1 Time series

The results so far show that there exists a cooling effect of the colony Johannisberg, which extends up to 80 m in the built-up area east of the colony, west of the colony even a extend of 160 m can be supposed. An additional measuring campaign with the mobile measuring device HuMVe was intended to confirm these results. For this purpose, fife one-hourly measurement runs were made from June 19, to June 20, 2017 along the Homburger Straße (cf. section 6.3.2). The additional measurements were used to check how well the air temperature data at a height of 2.5 m at the fixed sensors along Homburger Straße agree to the mobile measurements. This approach was important because the sensors on the colony borders could not be attached directly to Homburger Straße. Furthermore, the mobile measurements offered the possibility to measure in a higher spatial resolution. Finally, with the mobile measurements it was also possible to check how representative the selected measuring points of the fixed sensors were to a certain time of day. Fig. 35 shows the directly measured temperature distribution during the measuring runs (measuring route: cf. section 6.3.2, Fig. 17).

The measurement traverses shown in Fig. 35 demonstrate that the largest air temperature differences between the mobile measurements and the values of the fixed sensor occurred during the day, especially between 16 and 17 CET. At this time there is the largest difference of the HuMVe-measurments to those of sensor EAST_CB with a magnitude of 1.5 K. But also the deviations to CC in the centre of the colony and to WEST_CB are clearly pronounced with approximately 0.8 and 1.0 K. Higher values are thereby consistently measured by the fixed sensors within the colony, which is most likely due to solar radiation, which slightly overheated the sensors on the low-windy day, which had also just daily mean wind speed of 1.8 m/s. Outside the colony, on the other hand, the differences are lower with values between 0.2 and 0.5 K. In contrast, the deviations of the measured air temperature at night are, with the exception of sensor EAST_CB, very small (Fig. 35 c), d), e)).

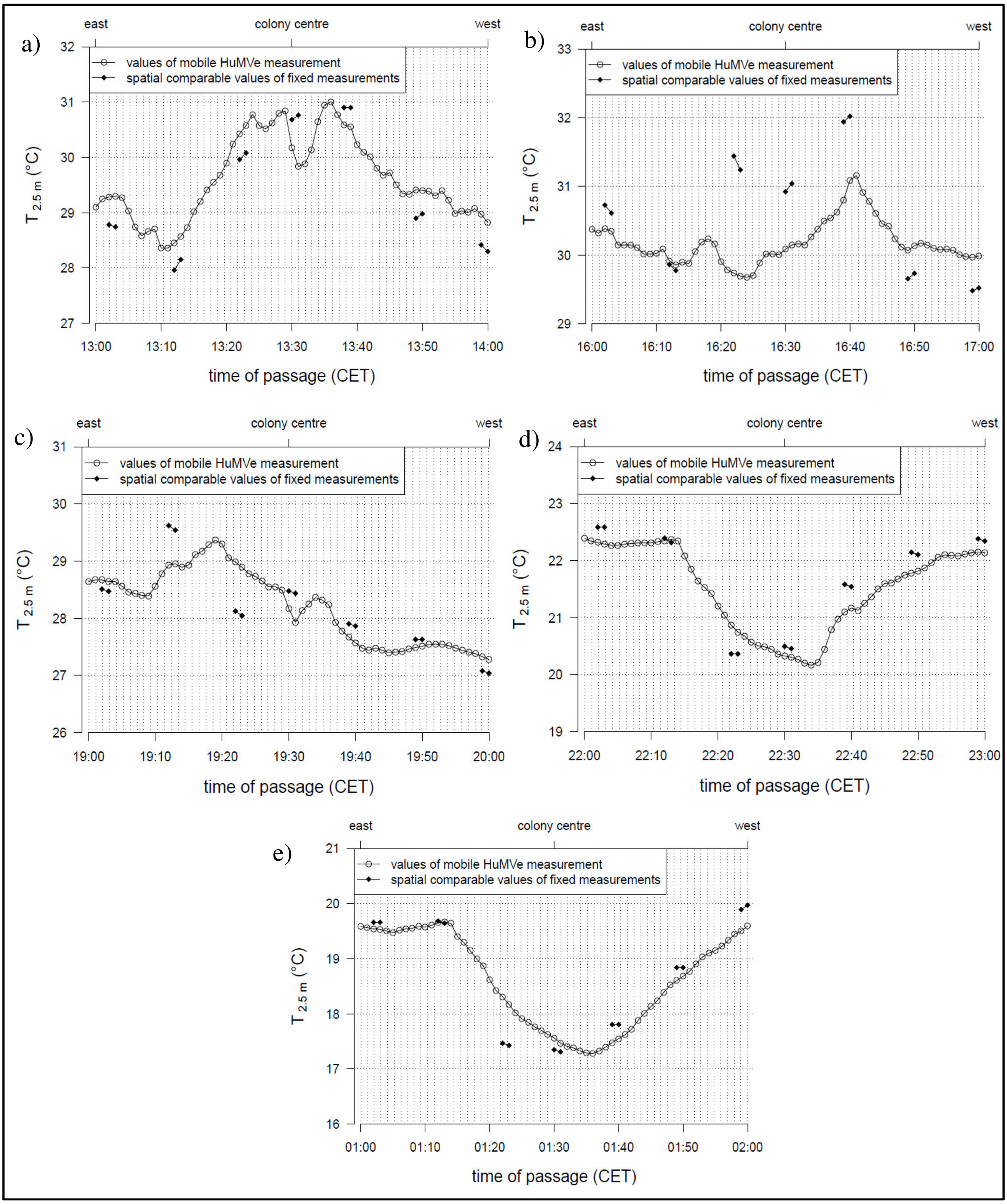


Fig. 35: Measured air temperature at a height of 2.5 m during the measuring traverses from east to west, shown as a time series of minute values together with the comparable minute values of fixed sensors: a) 13–14 CET, b) 16–17 CET, c) 19–20 CET, d) 22–23 CET, e) 1–2 CET.

Between 1 and 2 CET the deviations of the mobile measurements to the fixed sensors are the lowest, ranging from values below 0.1 K at EAST_80m to 0.3 K at the western centre area of the colony. Only at the eastern colony border the deviation between mobile and stationary temperature values was still at 1.0 K (Fig 34., at minute 22–23). To assess how well the measurement route of the mobile measurements reflects the values within the colony, the spatially and temporally associated values of the fixed sensors were correlated for each series of measurements. This results in the values in Table 7 for each measurement run. The results show that the values of the HuMVe measurements runs of 16–17 and 19–20 CET have the fewest matches with the values of the fixed sensors. Because only the 3 most easterly and westerly values per side are important for the study of the cooling effect on the residential area, the correlation was also carried out for these values. The results show that the values of the measuring routes in the west for all measurements carried out have in general a high correlation with the fixed measurements. In the east there is only a small, not significant correlation to the second and third measurement traverse, in contrast the other measurement runs show good results. With these results it can be stated that the results of the HuMVe-measurements and those of the fixed sensors both have a high expressiveness concerning the cooling effect along Homburger Straße at night.

Table 7: Correlation coefficients r of minute data from fixed and mobile measurements

Time	r of all comparable values from WEST_160m up to EAST_160m	r of all comparable values from WEST_CB up to WEST_160m	r of all comparable values from WEST_CB up to WEST_160m
13-14 CET	**0.922**	0.996	0.999
16-17 CET	**0.539**	0.984	-0.175
19-20 CET	**0.786**	0.976	0.271
22-23 CET	**0.952**	0.993	0.990
01-02 CET	**0.941**	0.996	0.996

To determine the results of the HuMVe-measurments on a spatial scale, the 2-minute-values at each of the 13 measurement points (cf. 6.3.2 and Fig. 17) were averaged. The same was done with the corresponding values of the fixed sensors (Fig. 15). Afterwards the points were allocated to their distance from the colony borders in Homburger Straße.

Of particular interest was the relationship with the wind, which was measured at a height of 3.0 m with the HuMVe since a microscale wind system is the decisive factor for the transport of the cold air of a green space into the adjacent built-up environment.

7.4.2 Temperature distribution and the local wind conditions nearby ground

In order to compare the distribution of the air temperature of the mobile measurements with the local predominant wind nearby ground level, the mean values of the air temperature at a height of 2.5 m were composed together with the wind which was simultaneously measured with the HuMVe at a height of 3.0 m (cf. section 6.3.1). The results for all 5 measurement traverses are shown in Fig. 36 and Fig. 37.

Fig. 36 shows the air temperature in a height of 2.5 m, the wind speed and wind direction measured with HuMVe during the first three measurement traverses. It must be mentioned that every measurement traverse lasted about one hour and for this reason the shown values are all measured at different times within each one-hour-lasting traverse. However, neighbouring values which are only about 5 to 10 minutes from each other should be good comparable. A combination with timely unified values was not realised in these figures since this was not possible for the wind.

Regarding Fig. 36, it becomes obvious that between 13 and 14 CET the wind nearby ground was very variable in its direction, whereby the wind velocity along Homburger Straße was almost in a dimension of 1 m/s. The observed superordinated wind at the DWD station Berlin Tempelhof was to this time from southwest (220 °) with a mean wind speed of 2.1 m/s. This direction was only observed at the central regions of the colony, whereas in the built-up area wind was mostly from western directions but with strong deviations. It becomes clear on the other hand, that it was warmer to this time in the area of the colony than in the adjacent built-up area. West of the colony a decrease of air temperature outside the colony with increasing distance towards the western residential area is visible. Due to the generally unstable atmospheric conditions in the UCL during day, a warming of the investigated urban neighbourhood by the colony Johannisberg can be excluded. Rather, it is conceivable that the air of the streets is led into the colony area, where it heats up.

The measurements of 16–17 CET (Fig. 36, b)) are more difficult to interpret. In general, it can also be stated that no overheating of the environment by the colony in the west can be determined. As in the case of the 13–14 CET (Fig. 36, a)), the western wind west of the colony speaks against any influence on the local development by the colony. On the other hand, the temperature rose slightly to the east of the colony for the first 39 m. The cause seems to be that the measurement point here was on the sunny northern side of the Homburger road adjacent to an irradiated building because a construction side prevented a measurement at the shadowed southern side of the street (Fig. 36).

However, during day existed no order in the wind direction, probably because of the daily convection in the unstable layering of the urban atmosphere during daytime.

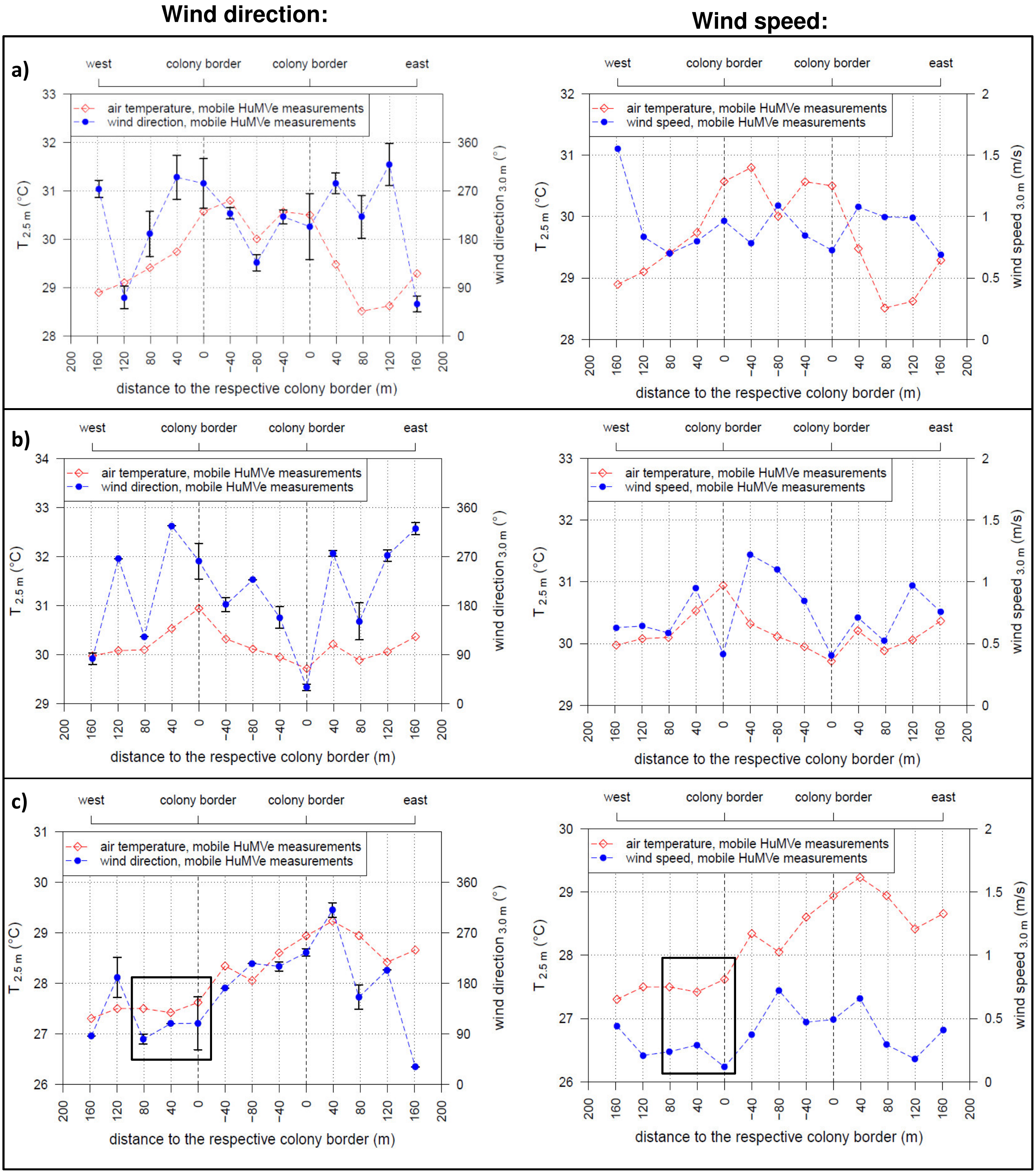


Fig. 36: Wind direction and wind speed measured with HuMVe during the day within the time periods 13–14 CET (a)), 16–17 CET (b)) and 19–20 CET (c)). The black rectangles mark regions where the development of a microscale wind system of the colony is supposed.

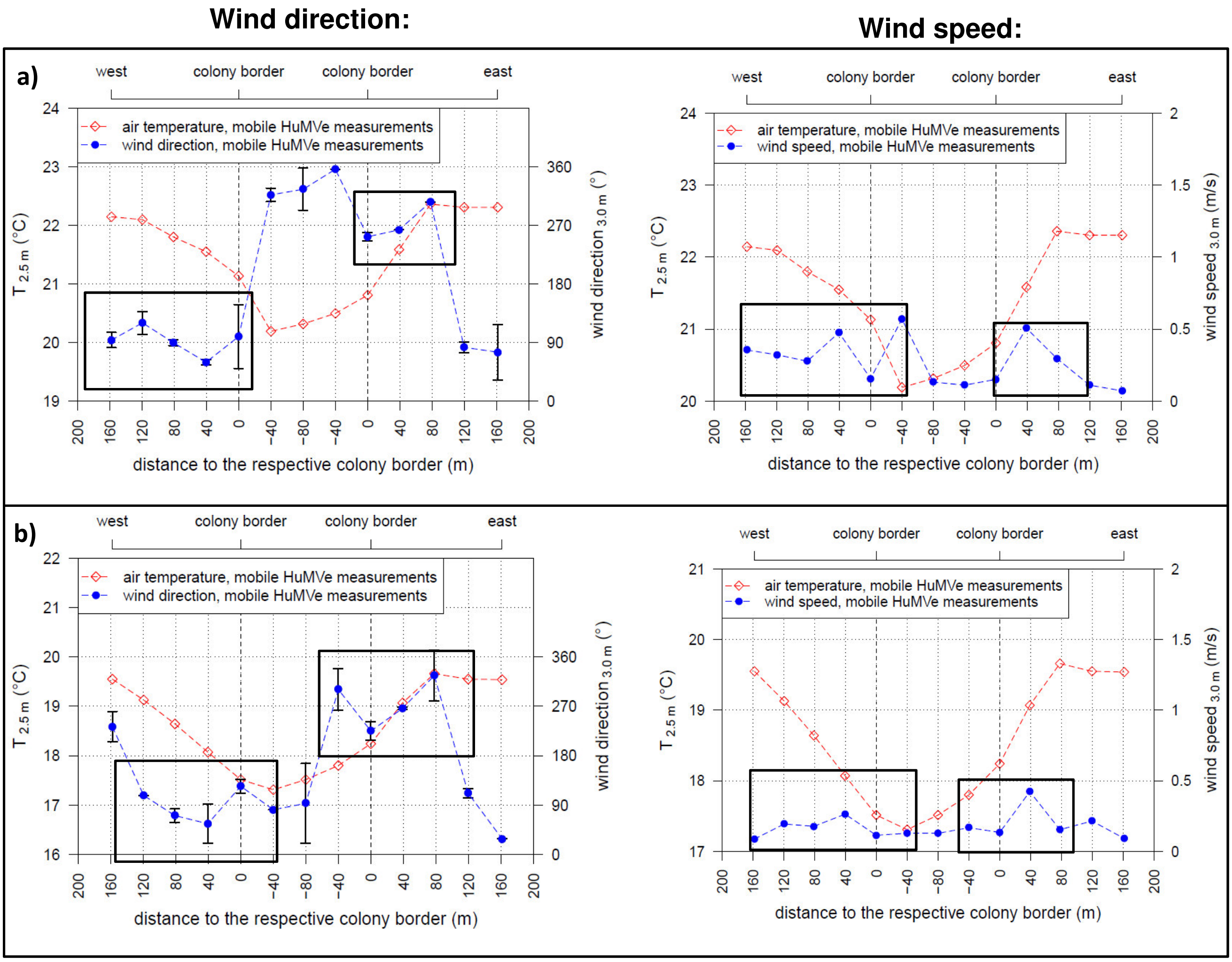


Fig. 37: Wind direction and wind speed measured with HuMVe during the night (June 19 to June 20) within the time periods 22–23 CET (a) and 1–2 CET (b). The black rectangles mark regions where a microscale wind system of the colony was observed.

For the topic of this work more interesting results were obtained from the measurements between 19 and 20 CET (Fig. 36, c)). Here, the development of a microscale wind system becomes obvious, which reaches from the western colony border at WEST_CB up to 80 m away at WEST_80m. Afterward it was temporarily interrupted by a south wind at a distance of 120 m and ended in an eastern wind again 160 m western of the colony. The wind speed of approximately 0.2 m/s–0.4 m/s underlines the presence of a microscale wind system which was briefly interrupted at the first bigger crossroads to Binger Straße, at a distance of approximately 100–130 m. The fact that the superordinated wind at this time was from western to southwestern and therewith opposite direction and comparatively slow (240 °, 1.9 m/s) confirms also a thermal generated wind system nearby ground level.

The course of air temperature in Fig. 36 irritates in this case due to the time shift during the measurement traverse. Fig. 38 shows with temporal extrapolated values that at 20 CET it was probable already 0.8 K colder at the western colony border than at the most western mobile measuring points, roughly 120 and 160 m further west in the residential area. For the areas east of the colony, an opposite wind regime is recognizable, although at that time it reached only about 40 m away from the colony (Fig. 36).

The resulting patterns of wind and temperature for the measurement traverses later in the night were at least as interesting as those during daytime. As can be seen in Fig. 37, the maximum wind speed near the ground in the study area between 22 and 23 CET was 0.5 m/s 40 m east of the eastern colony border and thus at the location opposite the construction site described in Fig. 17. The same phenomenon occurred western of the colony area about 40 m west of the colony border. The local maxima 40 m from the colony are maybe caused by channeling effects of the microscale wind system since in these distances the first buildings adjacent to the colony were present. West of the colony, the wind speed kept values between 0.3 and 0.4 m/s over the whole measurement distance of nearly 160 m, while it was significantly lower in large parts of the colony and over 100 m to the east of the colony (Fig. 37). In contrast, east of the colony a westerly to northwesterly wind occurred, which reached up to sensor EAST_80 m. Nevertheless, behind this station, the wind turned on little space by nearly 180 ° to eastern direction. The wind in the central area of the colony Johannisberg was with exception of one point in the western centre of the colony weaker and from northern to northwestern direction. Since the superordinated wind at this time period was from southwest and also weak (220 °, 1.4 m/s) and also due to the high daily air temperature of over 30°C and nearly 16 h solar radiation during daytime, stable conditions in the colony to this time are most likely. Thus, these values confirm the existence of a comparatively strong microscale wind system.

Similar conditions occurred at the last measurement traverse between 1 and 2 CET with the difference that the wind speed measured at 3 m height was obvious lower with values between 0.1 and 0.3 m/s western and eastern of the colony. The wind direction patterns have thereby also changed a little bit. Eastern of the colony, the pattern observed during the fourth measurement traverse from 22 to 23 CET can be found again, but with greater variability at a distance of 80 m. Western of the colony the microscale wind system kept continuous up to a distance of 120 m. Behind it, however, the wind direction changed to southwest. On the other hand the thermal introduced wind system also expanded also inside the colony, roughly to a depth of 40 m, whereby the same is true for the eastern area of the colony. Because the superordinated wind at this time came from west-southwest and was very slow (240°, 0.6 m/s), it can be stated, that also this measurement traverse also detected the microscale wind system of from the colony, which was however shifted a little bit to the colony centre. These results are very important, since they are the first of this kind at all.

7.4.3 Temporally corrected HuMVe measurments

Since it had been shown how far the directly measured cooling effect within certain short periods of time during the measuring traverses with HuMVe looked like and interacted with the wind nearby ground, it was interesting to know the course of temperature along Homburger Straße for a certain time step because the measurements were not taken simultaneously at each of the 13 measurement points, but within one hour. For this purpose, the mobile measurements were combined with the cooling rates of the fixed sensors along Homburger Straße. Therefore, the mean temporal cooling at the fixed sensor in the same height as the respective measurement location of the HuMVe between the two minutes of measurement and the end of the measurement traverse was used. For measurement points of the HuMVe between the sensors, the average of the temporal cooling rates of the two closest fixed sensors was used (cf. section 6.3.3). This procedure was used for every of the 13 measurement points. During daytime the values are connected with uncertainties due to fact that the solar radiation at the fixed sensors played still a big role, above all for the eastern measurement points, which have the bigger time differences to the final timestep of traverse to which is extrapolated. However, at night this approach should be reliable. The cooling rate of the fixed sensors which was expected to be similar to the corresponding measurement points of the HuMVe was added in order to finally get the conditions at the measurement route along Homburger Straße for the last time step per measurement traverse, namely at 14 CET, 17 CET, 20 CET, 23 CET and 2 CET. The obtained results are shown in Fig. 38.

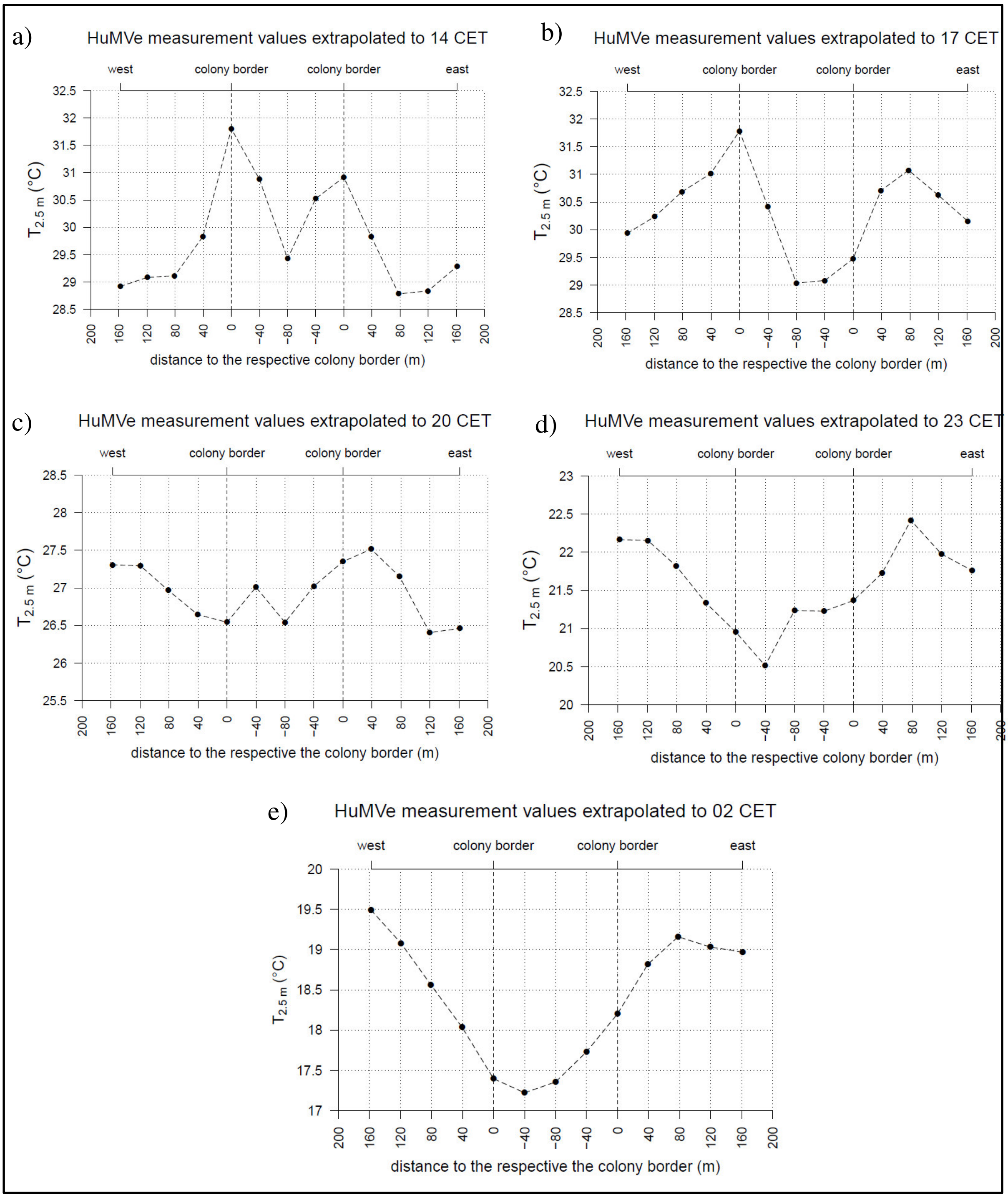


Fig. 38: Time-corrected curves of air temperature at a height of 2.5 m on basis of the measurement traverses with HuMVe and the cooling rates of the fixed sensors along Homburger Straße, extrapolated to the last time step of the measurement traverse.

Table 8: Values of time-corrected air temperature at 2.5 m height based on the HuMVe measurement runs. Green: Area of the colony, orange: Adjacent residential area.

measurement point number	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
colony border distance (m)	**157.9**	**119.4**	**80.9**	**40.5**	**0**	**40.0**	**80.0**	**40.0**	**0**	**39.0**	**78.0**	**119.7**	**161.4**
measurement 14 CET	28.9	29.1	29.1	29.8	31.8	30.9	29.4	30.5	30.9	29.8	28.8	28.8	29.3
measurement 17 CET	29.9	30.2	30.7	31.0	31.8	30.4	29.0	29.1	29.5	30.7	31.1	30.6	30.2
measurement 20 CET	27.3	27.3	27.0	26.6	26.5	27.0	26.5	27.0	27.3	27.5	27.2	26.4	26.5
measurement 23 CET	22.2	22.2	21.8	21.3	21.0	20.5	21.2	21.2	21.4	21.7	22.4	22.0	21.8
measurement 2 CET	19.5	19.1	18.6	18	17.4	17.2	17.4	17.7	18.2	18.8	19.2	19.0	19.0

The time-corrected measurements show a similar pattern along the Homburger Straße as the results of the fixed sensors (cf. section 7.3.3). However, there are also differences, firstly due to the higher spatial resolution, secondly by the fact that the HuMVe measurements were made in the area of the colony along the southern sidewalk of Homburger Straße and not in the colony itself. Since the Homburger Straße in the study area should act as a running path for the exchange of cold air, the results of the mobile measurements should be an important supplement for the investigation of the cooling influence of the colony Johannisberg.

The calculated values of temperature during daytime should be taken with caution due to the influence of solar radiation on the used cooling rates. Accordingly, the calculated overheating during day, especially for the time 14 CET, is most probably clearly exaggerated (Fig. 38 and Table 8). At 17 CET, however, it is interesting that the coldest air temperature along Homburger Straße was calculated for the centre of the colony with 29.0 °C, probably due to shadow on the sensor of the colony centre.

The calculated course of air temperature to 20 CET again showed a completely different picture (Fig. 38, c)). Here the highest air temperatures are meanwhile western and the eastern of the colony in the urban residential area and not in the colony itself. Summarised, the positive temperature differences between urban surrounding and colony Johannisberg show the decreased influence of direct solar radiation and the development of a temperature depression in the area of the colony Johannisberg. Thus, the ACI developed in this situation with a very warm night already in this time period.

Even more obvious patterns were existent at 23 and 2 CET, when the solar radiation no longer influenced the measurements and the wind near the ground showed also ordered structures over wide distances. For 23 CET the lowest values were calculated slightly west of the colony centre, about 40 m within the colony (Fig. 38 d)). In contrast in the eastern part of the measuring route inside the colony Johannisberg, higher values were calculated (Fig. 38 d)). The remaining air temperature values outside the colony confirm the measured ordered microscale wind system. They show on the one hand a relative strong increase of the air temperature of 1.0 K from the eastern colony border up to distance of about 80 m eastern of it and therewith up to end of the measured microscale wind system. Additionally, farer in the east of the adjacent residential area, a sudden decrease in temperature can be observed, probably produced by the playing ground in the height of sensor EAST_160m, at the eastern end of the measurement route. Western of the colony differences of up to 1.2 K were calculated between the colony border and measuring point 12, 120 m westerly of the colony at 23 CET. It should be considered that the low temperature difference between the two last measurement points in the west are a snapshot in time. Accordingly, the temperature differences shown in Fig. 38 are highly sensitive to the cooling rates at the resulting time differences between the measurement at the regarded point and that at the end of measurement traverse, here 23 CET. This cooling rates are, like the microscale wind system of the colony not a constant size and interact with the surrounding area.

A very good picture of the assumed ACI of the colony Johannisberg along Homburger Straße is given by the calculated course of air temperature for 2 CET. Here the cold spot at Homburger Straße in the western part of the colony occurred again like at 23 CET, but also the air temperatures along the eastern parts of the colony decreased. Altogether, therewith significant temperature differences could be measured between the colony and the adjacent urban built-up area. Over the 200 m distance from the local cold spot 40 m deep inside the western part of colony Johannisberg a nearly linear course of air temperature can be detected (Fig. 38, e)). Eastern of the colony on the other hand the pattern of 23 CET still exists, whereby the local maximum of air temperature 78 m eastern of the colony decreased compared to the further eastern measurement points.

Summarised, the results show clearly a cooling effect of colony Johannisberg along Homburger Straße for the night, which confirms the results of section 7.3.2. The cooling effect is thereby more pronounced west of the colony than to its eastern side. In the east, the results suggest a cooling effect, which extends 78 m into the development and weakens significantly at the eastern area of Rüdesheimer Straße (sensor EAST_80m). In addition, the second reference station to the east of the colony was fixed facing to a playground, which despite its many large trees influenced the temperature profile in its immediate vicinity. To the west of the colony, an extensive cooling effect from the colony could be measured, which builds up further during the night and is obvious with an air temperature difference of 2.3 K over a distance of 200 m.

The observations of the wind field lead to the localisation of a microscale wind system which explains the measured temperature differences. The described behavior course of temperature is confirmed by this and the four other investigated radiation nights. Therewith not only the cooling effect of the colony during mostly autochthone weather conditions is proven, but also the existence of an own specific microscale wind system of allotment garden areas, an “allotment breeze”.

8 Discussion of the results

This work examined the cooling effect of a Berlin allotment colony in the inner city of Berlin for 32 nights. The stationary measurements were additionally supplemented by five respective 1-hour-lasting mobile measurement traverses. It could be shown that the colony behaves similar to an urban park in terms of air temperature. Due to the relatively long continuous investigation period from May 31, 2017 to July 2, 2017 and the used measurement approach, the current state of knowledge on the influence of allotment gardens on the microclimate of the urban neighborhood could be significantly expanded and extended. The previous statement of research concerning the colony Johannisberg, that this area has no cooling effect on its adjacent urban environment, could be clearly disproved. However, to be able to better determine the research value of this work, it shall be compared in the following with preferably comparable works. Firstly, an overview of comparable works which also investigated allotment gardens should be given. Afterwards follows the discussion of the results, structured in the order of the results section.

8.1 Presentation of comparable works

Although there exist individual works that investigated the cooling influence of allotment gardens, their distribution and publication can be regarded as low. The recreational value of allotment gardens in the inner city of Berlin was rated as low by Horbert, 2000 based on mobile measurements done for an unpublished assessment in 1989. Therein, the strong cooling of a meanwhile demolished 1.4 ha wide colony nearby the city centre of Berlin was not interpreted as a beneficial factor for the inner-city climate, but as an indication of a lack of interaction with the urban built-up area.

The dissertation by von Stülpnagel, 1987, is the most frequently cited study related with the presentation of the cooling effect of allotment gardens in other works. However, the work from von Stülpnagel, 1987 studied also many other green areas in Berlin, whereby only one of these study areas is the “Schöneberger Südgelände/ Kleingärten Priesterweg”, an area which compromises a high number of direct adjoining allotment colonies grouped together and the area of a railway construction and an at that time partially used railroad shunting yard. For this 125 ha wide area 15 measurement runs were made during daytime and nighttime periods of April-December 1982 (von Stülpnagel, 1987). By usage of these results it was shown that the study area "Schöneberger Südgelände/ Kleingärten Priesterweg" was up to 5.4 K colder than its urban environment at a moderately low-exchange radiation night with a mean wind speed between 2 m/s and 4 m/s at 23 CET.

In the study, radiation nights were defined as days with a cloud coverage ≤ 4/8. In terms of the mean wind speed ($\bar{v}$), these were classified into three classes: Low-exchange nights ($\bar{v} \leq 2$ m/s), moderately low-exchange nights ($\bar{v} \leq 4$ m/s) and strong exchange nights ($\bar{v} \geq 4$ m/s). By this classification the work also examined the extend of the cooling effect at a height of 2 m. The extend of the cooling effect was thereby defined as the distance in which there exists still a gradient of 0.5 K to the urban environment. It turned out that the cooling effect of the area "Schöneberger Südgelände/ Kleingärten Priesterweg" in the nights in low-exchange weather conditions was 260–270 m and can be up to 1100 m windward in exchange-rich weather conditions.

However, the results of the high extend are also caused by the approach that other green spaces like the Insulaner, a wooded mountain of rouble in the south of the “Schöneberger Südgelände/ Kleingärten Priesterweg” were assumed as areas that extend the cooling effect instead of overlay or reinforce it. Due to this point and the fact that the investigated area was not only an area of allotment gardens, the range of the cooling influence is difficult comparable with this work.

The most important found work for a comparison of the results of this work was the dissertation from Farny and Kleinlosen, 1986, which examined among other topics the cooling influence of allotments in Berlin and involved several allotment colonies. In the work, the temperature effects of three individual allotment colony areas as well as the interaction of 3 neighbouring allotment colonies in Berlin were investigated. The work concludes that the micro-climatic conditions of allotment garden areas seldom reach into their surrounding urban area and are for this reason only rarely of importance.

One of the investigated colony areas in the work of Farny and Kleinlosen, 1986 was the allotment garden area "Oyenhausen" (Berlin-Schmargendorf). The measurement of the air temperature was carried out at four different time steps (12, 15, 18, 20 CET) on 23 July, 1983 with an aspiration psychrometer in a height of 2 m. In this case, a range of the cooling effect of 200–400 m was found to the southwest of the colony, with a cooling effect between colony border and the last meaningful measuring point of up to 2.7 K at 20 CET.

Also measurements for the here investigated colony Johannisberg (Berlin-Wilmersdorf) were implemented on 23 July, 1983, whereby three measuring runs (12, 15, 19 CET) were carried out. During daytime, the colony had a partly higher air temperature than its surroundings (0.6 K between measuring point 3 and 4 at 12 CET (cf. Fig. 39)). In addition, no influence on the first measurement point outside the colony, which was located about 100 m from the colony boundary, could be determined for the air temperature. The same course existed still at 19 CET, whereby the temperature difference between measuring point 3 nearby the colony border to measuring point 4 about 150 m southeasterly in the built-up neighbourhood was 2 K and decreased between measuring point 4 to measuring point 5 to 0.2 K. Since the temperature gradient on the measuring route dropped extremely from measuring point 4 to measuring point 5 in comparison to that between measuring point 3 nearby the colony border to measuring point 4 around 150 m southeasterly in the built-up neighbourhood, it was stated that the colony does not considerable interact with its urban environment and that the colony Johannisberg had no cooling effect on its urban neighbourhood.

Similar results to the environment showed for the colony "Gerickeshof" (Berlin-Moabit) based on four measurement runs on 23 June, 1983 (12.30, 15.30, 18.30 and 21:00 CET). Here, the nearest reference location was a gravel site of an adjacent commercial area. Behind this area no significant increase in temperature could be recorded anymore. However, at the 15.30 CET measurement period, the colony had a 1.8 K lower air temperature than the average air temperature the adjacent urban neighbourhood. These results differed little from those at 21 CET, when it was 2.0 K colder in the colony than in the adjacent built-up area. This for such urban green spaces untypical diurnal course of air temperature was reasoned by a superimposition of the climate prevailing in the colony by the adjacent urban climate (Farny and Kleinlosen, 1986).

In summary, the work came to the conclusion that allotments tend to develop a favorable climate function for themselves and that a cooling effect on the urban environment is possible if suitable ventilation paths are available. However, the observed cooling effect of 2–3 K at colony "Oyenhausen" was not given much importance because it occurred only in the evenings (Fary and Kleinlosen, 1986).

However, these results can hardly be compared with those of this work. An important reason for this is that although the mobile measurements of Farny and Kleinlosen, 1986 were assigned to a specific time, the actual time of the measurements and thus the time difference between the first and last measurements are not clear. Also, no information was given about the closer distances between the measurement points, which makes a comparison difficult. In addition, the measurements were performed only during the day and in the later evening hours, so that the night is not included as a period of maximum temperature differences. Finally, in the case of the colony Johannisberg an additional difference to this work was the implementation. As Fig. 39 shows, the measurement route for the colony Johannisberg was also shifted to southeast and not straight-lined, whereby the distance between measurement point 3 and 4 seemed to be in a dimension of around 150 m. Accordingly, it is not surprising that the measurement results of this work differ significantly from those of Farny and Kleinlosen, 1986.

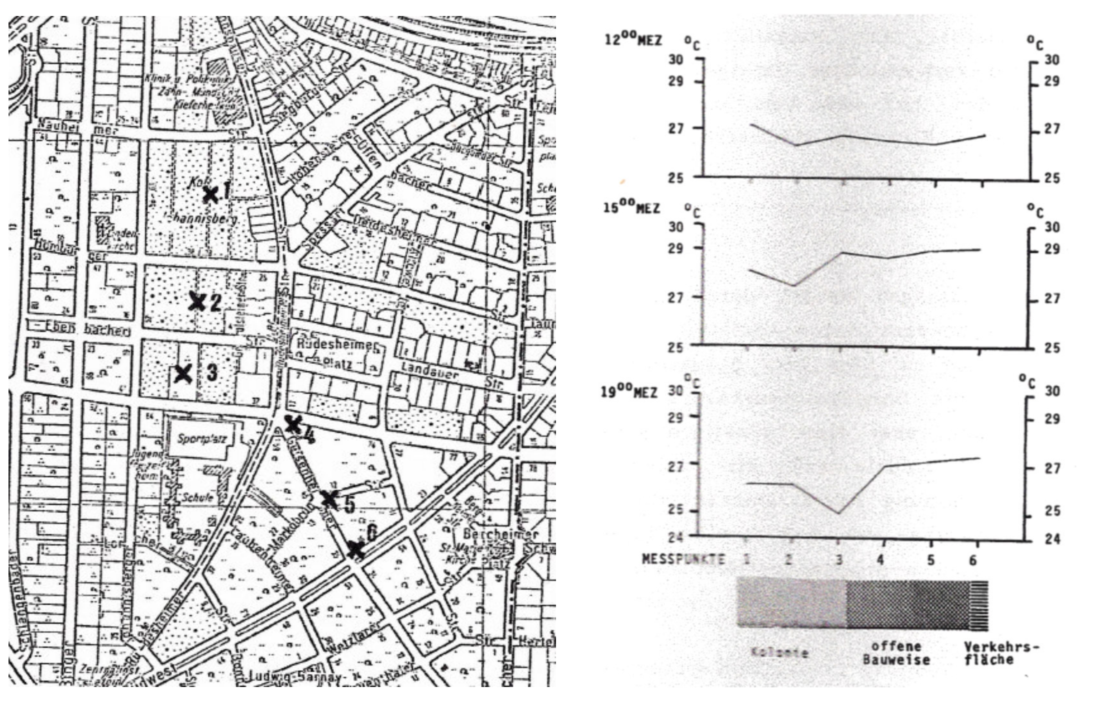


Fig. 39: Measurement points and the measured air temperatures at July 23, 1983 as result of the investigation of colony Johannisberg. Source: Farny and Kleinlosen, 1986.

In conclusion, some studies and results on the cooling effect of allotment colonies are already available. However, these are mostly over 30 years old and are mainly based on even older measurements. In addition, the results of these works only base on a few measurement runs, which were partly mostly realised during daytime. Consequently, the state of research for such an important topic is poor. For this reason, in the further discussion part, also park areas are used to estimate the beneficial cooling effect of the colony Johannisberg.

8.2 Comparison with the results of other works

Already for the mean over **all nights** it could be shown, that the average air temperature at the western colony border is clearly lower than at sensor WEST_160m, 157.9 m west of the colony (Fig. 25, Table 6). These results are highly informative as they cover 256 hourly averages and have been summarised regardless of the prevailing weather conditions. It turned out that 80.9 m west of the colony, it was 0.6 K warmer than at the western colony border, 157.9 m west this difference was 0.8 K. These values are quite remarkable for the 6.5 ha wide allotment garden area, as for the 111 ha wide Kensington Gardens in London a cooling effect was demonstrated which was in a 5-month average 1.1 K. This cooling effect is thus only 0.3 K higher than that of the colony

Johannisberg, although the park area is 17 times larger and additionally adjacent to the 142 ha wide Hyde Park (Doick et al., 2014). Doick et al., 2014 used the location, where 90 % of the maximal measured temperature difference between the park and the built-up environment were reached as border for the extend of the cooling effect, which was used for nights with organised temperature course and is therefore not comparable with the mean over all nights in this work. 78 m east of the colony it was in mean even 1.1 K warmer on the nightly average than at the eastern colony border. The effective temperature reduction by the cooling effect along Homburger Straße and the extend of the cooling effect can be hardly estimated for the whole period due to the lack of reference measurements at Homburger Straße leveled to sensor EAST_CB. Although a great part of the 32 nights was cloudy and windy, the colony showed a mean ACI intensity of 1.3 K, which was even never smaller than 0.3 K. The colony proved therewith to be also for a time period above one month an obvious cool island in Berlin.

For the five selected **radiation nights**, a significant cooling effect of the colony on its built-up urban environment could be shown. On average over all five investigated radiation nights, it was 1.2 K colder at the westerly colony border than at the sensor 78 m westerly and even 1.7 K colder than at sensor 157.9 m west of it. Since the resulting temperature difference in the built-up area between the two sensors WEST_160m and WEST_80m was on average 0.5 K, resulting in a mean nightly temperature gradient of about 0.5 K/80 m, a mean extend of the cooling effect of 80–160 m can be assumed, declining with increasing distance to the colony border. This is confirmed by a study that examined the cooling effect of 10 parks in Vancouver, Canada that also found a maximum range of cooling impact limited to one park diameter (Spronken-Smith and Oke, 1998).

However, the cooling effect also differs significantly within one and between the different radiation nights, because the ACI and the cooling effect linked to the "allotment breeze" must first build up within the night. Thus, the mean temperature differences to 20 CET are still at low and similar values, namely 0.8 K 78.9 m west and 0.9 K 157.9 m west to the western colony border. However, until the time period from 1 to 2 CET the differences increase to their average maximum. Then it was on mean over all radiation nights at the western colony border 1.5 K colder than in the built-up region 78.9 m western of it and 2.2 K colder than 157.9 m western of it. The strongest difference in air temperature between WEST_80m and WEST_160m occurred in the night from June 19 to June 20, the only night with a hot day with air temperatures obvious over 30°C in the investigation area. The night was specified by a nearly linear temperature increase from the western colony part to the western built-up area, whereby the temperature difference was in the second half of the night for several hours in a dimension of 1 K between the two sensors about 80 and 160 m western of the colony. In this night the minimal temperature at the warmest location in Homburger Straße was 19°C, whereby a proven cooling effect existed. For comparison the air temperature at the reference station in the Bamberger Straße was with 20.5°C 1.5 K higher at the same time. In contrast, in the colony centre the temperature minimum was 16.3°C. These numbers lead to the conclusion that allotment garden colonies are also an efficient way to reduce the occurrence of tropical nights, which are expected to increase in future also in Berlin (Umweltatlas Berlin, 2015).

The temporal behavior of the nocturnal ACI intensity and cooling influence of the colony with a maximum of each between 1 and 2 CET to the west and to the east of the colony differs obviously from the temporal PCI behavior that Spronken-Smith and Oke, 1998 discovered for different types of parks. In that work it is stated that mixed use, savannah and garden parks, which are most similar in shape to allotments, have a maximum PCI against sunset (in this work 20–21 CET) while open grass parks have their maximum temperature deviation to the urban environment towards sunrise (in this work 3–4 CET). This finding is confirmed by a one-year-lasting work which investigated the 10.3 ha wide Westpark in Dortmund, Germany with the result that the park had a maximal PCI in the first half of the night, around 21 CET.

The fact that the mean ACI intensity was already present 2 hours before sunrise, should be an indication that allotment gardens have a specific cooling behavior, which differs from park areas. However, since also the outer sensors in the urban neighbourhood can be influenced by the cooling effect of the colony, the temperature difference between the coldest point in the colony and the reference sensor at Bamberger Straße (BS) should give a better estimate of the time of the temporal occurrence of the maximal ACI (Fig. 40). The values in Fig. 40, which are equivalent to the maximum of the defined cooling effect inside the colony confirm the statement of an observed maximal ACI intensity which differs in time from that of urban parks. Also here the maximum temperature difference between the colony Johannisberg and the reference station is still clearly before sun rise and also definitely not to beginning of the night. In mean it occurs between 1 and 2 CET and therewith to the same time as the maximum temperature difference between the urban environment and the adjacent colony border area ΔT_{i-cb} (cf. Fig. 28).

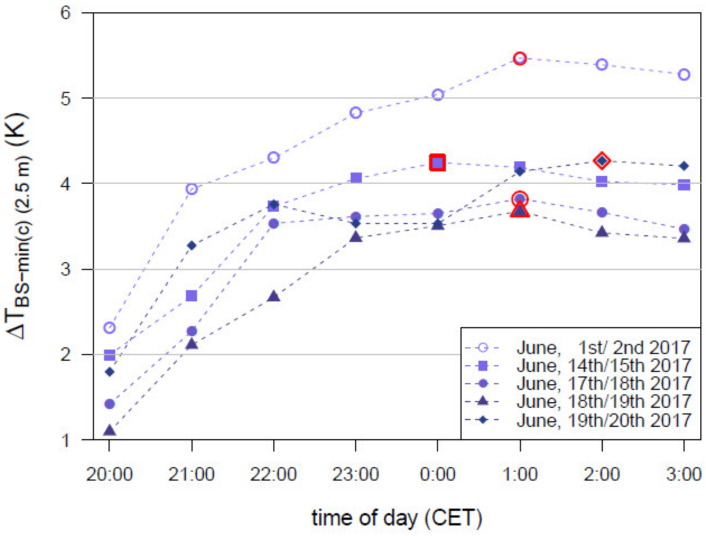


Fig. 40: Occurrence of the maximal difference of air temperature between the station BS and the minimal air temperature inside colony Johannisberg for the five investigated radiation nights. The red borders mark the respective maximum.

A probable cause for this is the partial sealing of allotment areas. For colony Johannisberg a sealing degree of 15% was estimated which should slow down the cooling of the area in the first hours after sunset. This should explain the temporal difference in the occurrence of the PCI for mixed use, savannah and garden parks that reached its maximum around sunset (Spronken-Smith and Oke, 1998). Another reason should be the special vegetation composition of the allotment gardens, which consist for example by many low fruit trees and hedges, which in turn could damp a further strong until sunrise. The high significant correlation between the maximum of the defined cooling effect and the UHI intensity (Fig. 41) underlines the informative value of the results in Fig. 40. Additionally, Fig. 41 shows that the maximal temperature difference between colony Johannisberg and the station BS and therewith the maximal assumed cooling effect of the colony is roughly of about the half dimension of the UHI intensity. Since BS should be not influenced by any cooling effect due to a lack in vegetation in its surrounding, Fig. 41 demonstrates even more the existence of the ACI and proves that it increases significantly with the UHI.

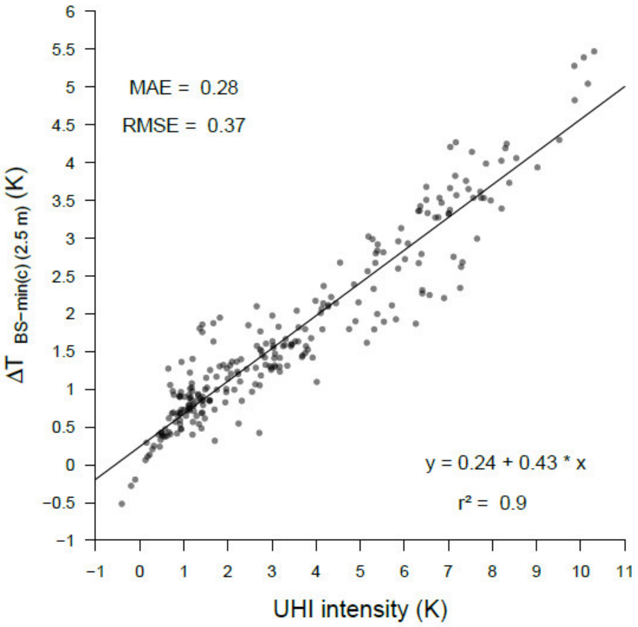


Fig. 41: Linear regression between the defined maximal cooling effect and the UHI intensity.

To ensure that the colony really cools its urban surroundings, in addition, between June, 19 and June, 20 2017, five **mobile measurements** with the HuMVe were carried out. These confirmed the already estimated maximum extend of the cooling effect of approximately 80 m to the east and 160 m to the west to the concerning borders of the colony Johannisberg. Furthermore, the development of a microscale wind system, the in this work named “allotment breeze” could be observed, which reached wind speeds between 0.1 and 0.5 m/s during the night. A study in Göteborg, Sweden measured a thermal introduced breeze of 0.3 m/s for a temperature difference of 2.5 and 3.8 K between the investigated area and its urban surrounding (Thorsson and Elliason, 2003 in Bongardt, 2006). Bongardt, 2006 calculated for a measured PCI of 3.9 K in his work a theoretical maximal park breeze speed of 0.5 m/s but could not measure the wind system directly. Along Homburger Straße an allotment breeze of 0.4 to 0.5 m/s could be observed temporarily, which lead to the assumption that the maximum temperature differences between the residential area and the colony were remarkable higher than the measured ones. Another cause could be that the superordinated wind gave an impulse at the probably partially western directed upper part of the allotment breeze circulation system which lead to an accelerated outflow of the cold air nearby ground level.

However, Thorsson and Elliason, 2003 could measure the wind system of their study only for the measured high temperature difference and only under very stable

atmospheric conitions with a snow cover above the study area and only in winter time. Thus, this work may be the first that measured a thermal breeze direct during summer time and is very probable the first that proved the existence of an allotment breeze.
The mobile measurement additionally showed that the location of the sensor EAST_CB on the eastern colony border is not very representative for the investigated course of air temperature along Homburger Straße during nights, because the measured values there were about 0.5 K to 1.0 K lower than at the reference values measured at point 5 of the mobile measurements with HuMVe. This was probably caused by its position, 12.2 m south of the HuMVe measurement route. Further reasons for these differences could have been the construction area and the presence of an arbour nearby the HuMVe measurement point 5, leveled to the fixed sensor EAST_CB, which reduced the outflow of cold air here to Homburger Straße. Nevertheless, the measured wind pattern clearly confirms the flow of the air inside the colony Johannisberg eastward towards the eastern side of Rüdesheimer Straße. Consequently an existing, but weakened cooling effect due to the numerated factors should be supposed here. Finally, the mobile measurements confirmed the measured temperature distribution of the remaining fixed sensors. Also, the nearly linear temperature distribution at the night from June 19 to June 20, 2017 is now better understandable, taking a ground-near enclosed allotment breeze into account.

The highest differences of air temperature between colony border and urban neighbourhhood of 2.8 K (2.4 K) occurred together with the maximum ACI intensity of 3.2 K (3.0 K) in the night from June 1 to June 2 (June 19 to June 20), respectively after a sunny and dry weather period. Thus, for the with 17.6 hectares much larger multi-use Stadtpark in Berlin-Steglitz at 23 CET, only a PCI of 1.0 K was determined for a moderately low-exchangeable night in July (von Stülpnagel, 1987). A PCI of 1.0 K was also demonstrated for the 6-hectare Kleistpark in Berlin, which, like the Stadtpark-Steglitz, is mainly covered with grassy areas and individual groups of trees. Both values refer to a measuring height of 2 m. For the Stadtpark in Berlin-Steglitz it could also be proven that the range of its cooling influence decreases with increasing building density and reaches in low-exchange radiation nights an extend of 60–140 m (von Stülpnagel, 1987). The results of a study of parks in Canada showed that parks of similar size to the study area can also have significantly higher PCI values. For example, the 4.86-hectare, predominantly grass-covered, Trafalgar Park in Vancouver showed a PCI of up to 5 K and a cooling effect of 200–300 m range (Spronken-Smith and Oke, 1998; Bongardt, 2006). However, since the work of Spronken-Smith and Oke, 1998 used the maximum urban air temperature as reference for the calculation of the PCI such high values were also reached in this work, in case of considering the maximal difference of air temperature between the colony and station BS, which reached up to 5.5 K (Fig. 40).

In addition, the work of Spronken-Smith and Oke, 1998 showed that treeless, free and dry surfaces cool the most at night. The statement that the PCI of urban parks usually reaches between 1 and 2 K, rarely up to 3 K (Spronken-Smith and Oke, 1998) is confirmed by two further investigations from Germany. A one-year survey of the 10.3 ha wide Dortmund Westpark showed that the area had on the average of more than 50 autochthonous weather conditions a maximum PCI intensity at 21 CET of 1.7 K, which becomes slightly lower during the night again (Bongardt, 2006). During summer the PCI of the Dortmunder Westpark can reach under autochthonous conditions values remarkable above 2 K. For a low-exchange summer night in August, the work showed a maximum PCII of 3.6 K at a height of 3.5 m. This result agrees well with the maximum ACII of this work of 3.2 K at 2.5 m height between the colony centre and the residential area western of the colony. The results are also interesting because the examined 10.3 ha wide Dortmunder Westpark has with a mean edge length of 430 m from north to south and 240 m from east to west a similar rectangular shape and orientation as the colony Johannisberg. Furthermore Bongardt, 2006 also used for the definition of the PCI the original approach of Spronken-Smith, 1994, whereby the PCI is the temperature difference between urban the highest measured temperature in the urban neighbourhood and the lowest air temperature in the park. Thus, and due to the fact that Bongardt, 2006 used 30-minute-averages and this work 1-hour-avergaes, it can be stated that the cooling effect of the colony Johannisberg is at least temporarily comparable to that of the greater Dortmunder Stadtpark. The results are also similar to the measured temperature difference between the border area of the 30 ha wide colony areas, summarised under the name colony “Oyenhausen” and its urban neighbourhood (Farny and Kleinlosen, 1986). However, the therein measured temperature difference of 2.7 K is difficult to compare with this work, since the original time of measurement is not known. Anyway, the statement of Farny and Kleinlosen, 1986 that colony Johannisberg does not cool its urban surrounding could be clearly disproved. The statement would certainly not exist, when the measurements of 1983 would have been carried out at night with the first measurement points closer and not shifted from the colony (cf. Fig. 39).

Table 9: Overview of the results of this and the compared works of the discussion part

size (ha)	city (country)	latitude (°)	green space	structure	neighbourhood	cool island intensity	extension of cooling effect	occurrence of maximum cool island	reference
6.5	Berlin (Germany)	52	Kolonie Johannisberg	allotment gardens	perimeter block development, terraced houses (N, E,W), playing ground (S)	3.2 K (01 CET) (mean: 1.3 K)	80-160 m	maximum in mean 2 hours before sunrise between 1 and 2 CET	This work
4.86	Vancouver (Canada)	49	Trafalgar park	gras, trees at borders	single family residential housing (suburban)	5.0 K	200-300 m	maximum soon after sunset	Spronken-Smith and Oke, 1998; Bongardt, 2006
6.5	Berlin (Germany)	52	Kolonie Johannisberg	allotment gardens	perimeter block development, terraced houses (N, E,W), playing ground (S)	2.0 K (19 CET)	not detectable (0 m)		Farny and Kleinlosen, 1986
10.3	Dortmund (Germany)	52	Westpark	groves, gras areas	perimeter block development (N,E,W), suburban railway (S)	3.6 K/ 3.9 K (stations/mobile) (mean: 2.2 K)	max. 240 m	maximum in first half of the night, in mean at 21 CET	Bongardt, 2006
17.6	Berlin (Germany)	52	Stadtpark-Steglitz	mulit-used	perimeter block development/terraced houses (N, E,S), detached houses (W)	1.0 K (23 CET)	60-140 m		von Stülpnagel, 1987
30.0	Berlin (Germany)	52	Kolonie „Oyenhausen“	allotment gardens	perimeter block development, terraced houses (E,S,W), playing ground (N)	2.1 K (20 CET)	200 m		Farny and Kleinlosen, 1986
111	London (England)	52	Kensington Gardens	mulit-used	perimeter block development, terraced houses	4.0 K (mean: 1.1 K)	440 m (mean: 125 m)		Doick et al., 2014
125	Berlin (Germany)	52	Kleingärten Priesterweg/ Südgelände	allotment gardens	mixed urban landsacape: highway area (N), industrial area (E), park (S), perimeter block development (W)	5.4 K (23 CET)	500 m (mean: 270 m)		von Stülpnagel, 1987

8.3 Presumptions concerning the allotment breeze of colony Johannisberg

The existence of an allotment breeze, which advects the cold air from the colony to its urban neighbourhood is already proven in this work. This part shall only summarise the assumptions of the structure of this wind system for a better imagination.

How far the cooling effect of the colony extends beyond the outermost measuring point west of the colony cannot be stated with certainty in the results of this work. Like the measurements in Fig. 36 and 37 indicate, the allotment breeze is not a constant size. The allotment breeze varies depending on outer influencing factors like the air temperature and therewith pressure differences, its own wind speed and impulse which can increase its stability and ordered structure and it underlies the influence of the superordinated wind. In this context it is mostly probable that the broad north-south-oriented streets Schlangenbader Straße in the west and Aßmannstraße/Rüdesheimer Straße to the east create a barrier for the cooling effect of the colony Johannisberg at the height of Homburger Straße, which is only rarely overcome and when then with little effect. For this reason, the air temperature at the station BS used to determine the cooling effect seems to be an upper limit, which could be reached more within the high-rise complex on the west side of Schlangenbader Straße (Fig. 10, Fig. 11) than in a radius of 160 m around the colony. This should be partially also caused by the allotment breeze, which advects cold air along Homburger Straße. Under the assumption of Schlangenbader Straße as a barrier to the influence of cooling, the cooling effect of the allotment garden Johannisberg could reach a maximum extend of up to the Schlangenbader Straße, about 190 m west of the colony. This is supported by the subsequent interruption of the cold air train through the 25 m wide road and a large residential high-rise building complex adjacent to its western side (cf. Fig. 10, Fig. 11).

The assumptions about an extend of the cooling effect by colony Johannisberg of 160 m to the west and 80 m to the east are confirmed by mobile measurements with the HuMVe. In a situation with an "allotment breeze" (cf. Fig., 36 and 37), the HuMVe measurements show a clear wind shift from western to eastern direction 80 m east of the colony. Probably due to an underestimated effect of the playground area or more probably as compensation flow, a further wind flow could be detected in a height of 3.0 m, in fact in opposite direction to the "allotment breeze" roughly 80–160 m eastern of the colony. This underlines the assumption that the cooling effect reached up approximately 78 m east of the colony. But it also leads to presume that the crossroads at Rüdesheimer Staße (sensor EAST_80m) as the warmest local place in this region acts mostly as border between the allotment breeze of the colony and a weaker opposite air flow, which is produced most likely not by the small play-ground area itself but due to the low pressure area resulting by the rise of the air at the crossroads of Rüdesheimer Staße caused by the most probably unstable layering conditions in the UCL here. Although the Schlangenbader Straße in the west and the Rüdesheimer Straße in the east are assumed to be the limit of the cooling influence of the colony Johannisberg in height of the Homburger Straße, both roads could also contribute to the emergence of the park breeze of the colony Johannisberg. Due to the high sealing of both areas of estimated 80–90% with stone, concrete and asphalt and the big surface that can absorb sun radiation, a lot of heat energy should be stored here during the day. At night these areas should release in turn high amounts of sensible heat and lead to a warming and uprising of the colder air, advected with the allotment breeze. Fig. 42 shows the own imagination of the structure of the allotment breeze measured in the night from June 19 to June 20 2017 at its maximum extend:

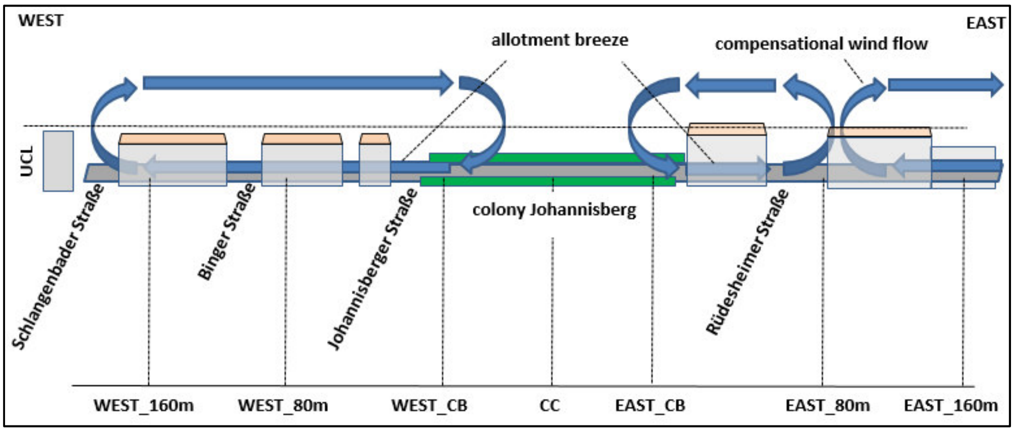


Fig. 42: Scheme of the allotment breeze along Homburger Straße on basis of own measurements and on the scheme of Gunawardena, 2017.

North and south of the colony, the effect of cooling was not investigated because measurements were concentrated west and east and within the colony. Because the extent of the colony in north-south direction with approximately 420 m is clearly larger than in west-east direction (height Homburger road approx. 160 m) it can be assumed that locally high extends of cold air advection are possible, above all there, where the colony is in the same height level or even higher than its surrounding (cf. von Stülpnagel, 1987). A wide extending cooling effect can be expected especially along the

Johannisberger Straße to the north and the Aßmannstraße to the northeast, where the cold air can easily spread at night (Fig. 10, Fig. 11). How far the cooling effect at night in these directions reach cannot be estimated here. However, it is probable that it should have a similar range to the north in the area of Johannisberger Straße as in the west of the colony (Fig. 11). In contrast, it should be lower south of the colony, since the southern colony area is mostly 1–3 m below the street level and therewith a high amount of cold air should accumulate inside the colony before it flows out in southern direction (cf. Fig. 9). The fact that north and south of the colony no streets are designed as potential cold air corridors in the centre area of the colony could in turn reduce the expansion of cold air into the urban development.

8.4 Connection between cooling effect and the superordinated wind

An entrainment of the nocturnal cold air with the superordinated wind field, which significantly reduced the nighttime temperatures in the urban environment around the colony, could not be observed., contrary to literature research (Oke, 1989; Bongardt, 2006). In contrast, the effects were mostly inside the colony area along Homburger Straße, where for eastern and southern winds of 2–4 m/s it was obvious colder in the eastern part of the colony than in its centre and western area. These effects however, occurred probably due to turbulence effects which were in the east of advantage for the preservation of the local cold air, whereas farer in the west warmer air, perhaps from the UBL was advected (cf. Fig. 43). The occurrence of an isolated roughness flow in the colony is possible, because it occurs, when the aspect ratio of building height to building with (H/W) is below 0.3 (Oke, 1987), what is true for the colony.

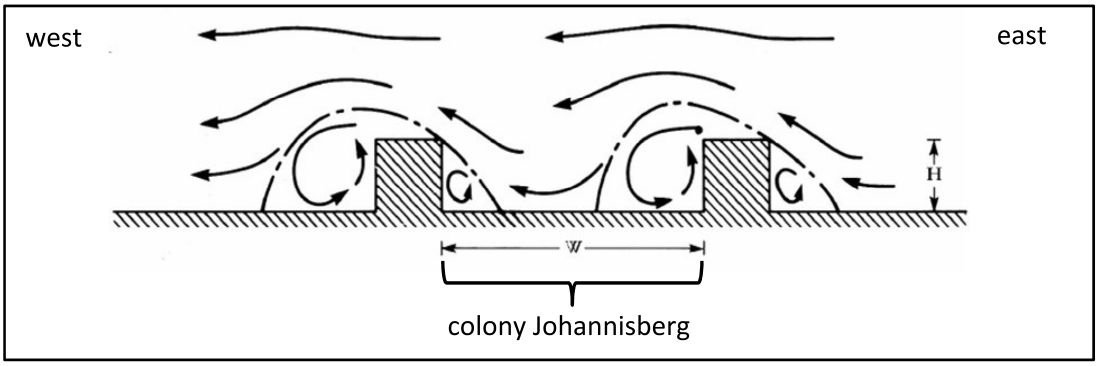


Fig. 43: Streaming pattern above city structures with H/W < 0.3 as scheme of the supposed wind pattern in the UCL in the area of the colony Johannisberg during nights with easterly winds of 2–4 m/s in a height of 10 m. Source: Oke, 1987, altered.

The results of wind speed situation above 4 m/s were on the other hand not useful, since the local temperature differences became mostly negligible.

In contrast to those work, Oke, 1989 determined for a 38-hectare park in Montreal at wind speeds of 2 m/s at the end of May, a cooling effect of several hundred meters was found. In this context, many reasons are assumed for the fact that the superordinated wind did not transport the cold air of the colony into the urban environment: Firstly, the diameter of the colony in the examined section of 160 m is not very large. The 10 to 20 m high buildings near the colony border could have interfered with the entrainment of cold air by the formation of vortexes. Also the 6 to 15 m high trees along the Homburger Straße should also have deflected the superordinated wind direction significantly in the area under the treetops and therewith changed the wind conditions nearby ground so that no ordered advection was possible anymore.

However, an important result was that a superordinated wind rectangular to the measurement setup interrupts the allotment breeze and lead in the residential area western of the colony to nearly homogenous air temperatures (cf. Fig. 31, Fig. 34). Thus, although a significant advection of cold air into the urban environment with the superordinated wind could not be detected, its investigation indicates indirect that the allotment breeze also existed in all other radiation nights. The deviating course of air temperature along Homburger Straße for situations with wind speed above 2m/s and rectangular to the measurement device to the temperature courses of the five investigated radiation nights is supposed to be caused by an interruption of the allotment breeze.

8.5 Relevance of the results for Berlin

In this work it could be shown that the allotment garden colony Johannisberg represents by its nocturnal cooling effect an important microclimate regulating area in the inner-city area of Berlin. As allotment gardens in Germany are similar in their general appearance due to the regulations summarised in the Bundeskleingartengesetz, a similar effect can be assumed for allotment gardens of comparable size and similar urban environment. Nevertheless, allotment colonies differ slightly in their location in the city, their use (Farny and Kleinlosen, 1986) and their sealing degree. The density of buildings and the structure of their urban environment and the existence of cold air pathways also influence the range of the cooling effect (von Stülpnagel, 1987). As a result, the temperature differences cannot be directly transferred to similar colonies. For

Berlin, the results are important because the number of allotments in Berlin has declined significantly in the last 20 years. Approximately 85 –90% of allotment gardens over 30 years ago in West Berlin were located in moderately overheated areas of the city about (Farny and Kleinlosen, 1986). Up to 2020 Berlin's goal is it to receive 83% of the current allotment area (Senatsverwaltung für Stadtentwicklung und Umwelt, 2015), which also means that 17% of the area can be used differently, thus a further decrease of allotment gardens in Berlin is most probable. However, Berlin will also face great challenges in the future. On average, a further increase in Berlin's population to 3.828 million inhabitants up to 2030 is predicted, according to an increase in the population of over 200,000 people compared to the population at the end of 2016 with 3.671 million people (Amt für Statistik Berlin-Brandenburg, 2017). The amount of the increase is strongly determined by the immigration quota by refugees and is correspondingly difficult to estimate (Amt für Statistik Berlin-Brandenburg, 2017). This development is superimposed by an increasing average age of the population.

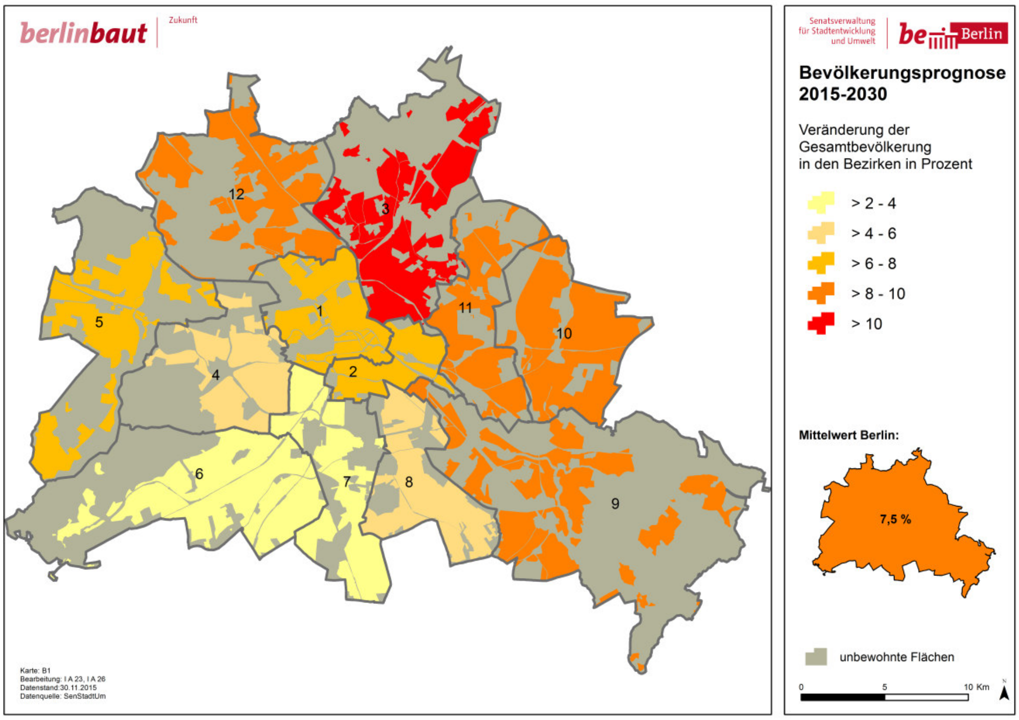


Fig. 44: Predicted population growth between 2015 and 2030 for Berlin in percent. Source: Senatsverwaltung für Stadtentwicklung und Umwelt, 2016.

The number of people in an age group of 65 to 80 is expected to rise by 12% to around 581,000, while the number of people over the age of 80 will rise by almost 62% to around 263,000 (Amt für Statistik Berlin-Brandenburg, 2017). The distribution of this predicted development is shown in Fig. 44 and Fig. 45. Between 2015 and 2030 population growth of 4–6% is predicted around the study area, which is associated with an increase in population of the age group above 65 by 10–20%. Although the population growth is associated with an increased need for space, the creation of open spaces in the inner-city area by demolishing allotment areas should be stated clearly as a negative and shortsighted solution. This argument is underlined by the fact that allotment gardens are most needed in the inner area of the city because of their benefits by their UES, what is also true for their nightly cooling function.

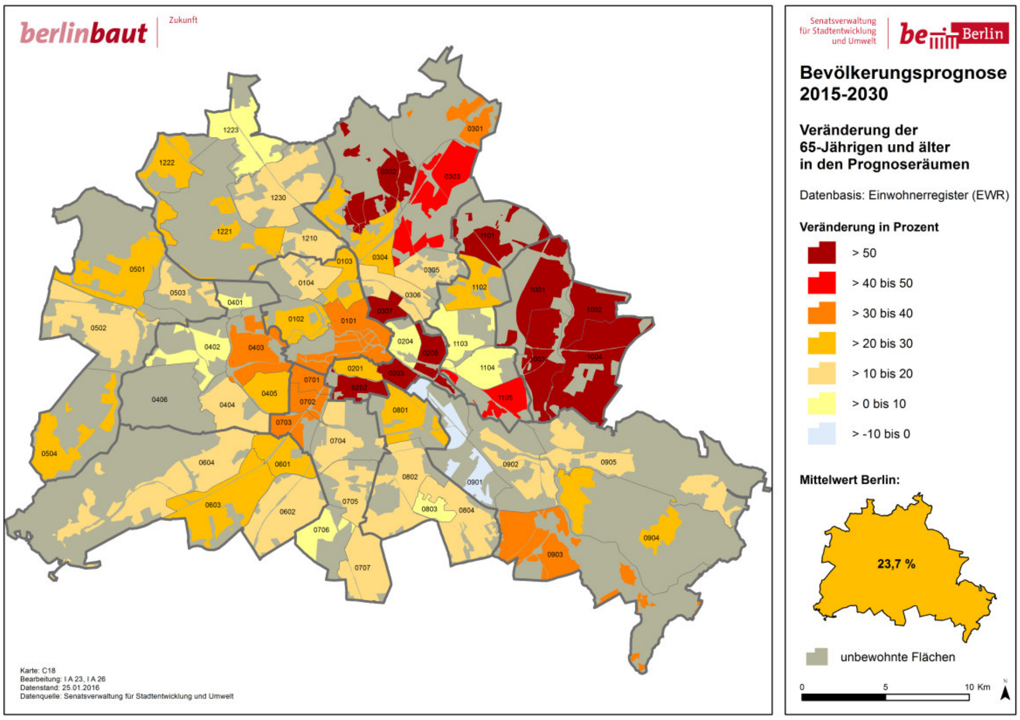


Fig. 45: Predicted population growth of the age group above 65 years between 2015 and 2030 for Berlin in percent. Source: Senatsverwaltung für Stadtentwicklung und Umwelt, 2016.

The increasing number and simultaneous aging of the urban population in Berlin makes this approach even more relevant, as the importance of lowering the UHI is growing additional with the growing proportion of older people. More important than thermal comfort is thereby that risk groups of people above 65 years can react with a higher mortality on heat stress. For Berlin it could be proved that 5 % of the cases of death within the period from 2001 to 2010 could be statistically attributed to higher mean air temperatures (Scherer et al., 2013). This point should be taken seriously, as an increase in air temperature can increase the mortality rate, especially of at-risk groups, while lowering the air temperature by a few Kelvin can have a positive impact on health

(Clark and Bach, 1971 Höppe, 1991). Due to the high density building structure and the increased heat load by the UHI in the city centre area, it is important to protect the remaining allotment garden areas and to promote the creation of new allotment garden areas in context with new construction projects. The numerous UES of the allotment gardens are together with the now proven cooling effect a meaningful planning instrument for a sustainable human, animal and plant friendly cityscape, which at the same time improves the inner-city climate.

8.6 Importance and transferability of the results

The results of the present work are in a strong contrast to the current state of knowledge, according to which the investigated colony Johannisberg has no verifiable cooling influence on its urban environment (Farny and Kleinlosen, 1986). Instead the present work stated that the colony is as a significant nocturnal cool island, with an ACI intensity of the same or even greater magnitude than that of some of the surveyed 3 to 17 ha wide parks mentioned in this work. The nocturnal drop in temperature caused by the colony, which is detectable in radiation nights at a height of 2.5 m up to a distance of 160 m, should improve the well-being and sleep quality on nights with increased heat load. The cooling effect of the colony Johannisberg should also have the potential to positively affect the health of risk groups such as the elderly people. Also, the allotment area may have the potential to reduce the risk of mortality by lowering the minimum and mean temperatures during pronounced heatwaves (cf. Dousset et al., 2011; Scherer et al., 2013). It was also found out that the ACII and the cooling effect of the colony correlate significant with the UHII and the ACII and the cooling effect increase with a rise in the UHII. Consequently, the ACII is most pronounced when it is most needed.

Colony Johannisberg is with 6.5 ha in the size range of 5–15 ha, from which on city parks have a year-round effect on their urban environment and not only under special conditions form their own climate (Horbert, 2000). Thus, the climate impact of the colony should also be year-round like indicated by the 32-night-lasting investigation, its climatic benefits are strongest during radiation nights, especially in the summer months. Since 90 % of the European urban green spaces are smaller than 15 ha (Bongardt, 2006), colony Johannisberg presents a size class of a green area, which dominantly exists in European cities. Furthermore, allotment gardens are a widespread land use form in Germany (Bundesverband Deutscher Gartenfreunde e.V., 2017) but also in other European urban areas, above all in Poland and England (Office International du Coin de Terre et des Jardins Familiaux a.s.b.l., 2017; Speak et al., 2015). Therewith the cooling effect of allotment gardens has also an international value. Here in turn the regional and national differences in the construction of allotment gardens should play a deciding role on their UES and the ACI.

8.7 Outlook

In order to be able to assess the cooling effect of allotments close to the city centre, further measurements on site have to be made. Because of the differences between the surface characteristic of allotment garden areas and park areas, results found for urban parks work cannot easily be transferred to other colonies. Also because the construction of allotments in a sense represents a transition of land cover between parks and detached houses or expressed in local climate zones between LCZ 6 “open low rise” and LCZ B “scattered trees”, the area should not be compared with that of a park. This and the fact that individual allotment gardens itself are in contrast to the most area of a park not public underline this difference. However, it can be assumed that allotment gardens have with increasing size like parks a greater cooling effect. The meaningful term "Allotment Cool Island" (ACI) which interacts by the “allotment breeze” with its urban neighbourhood are powerful terms, on which the allotment gardens can invoke in future. The terms are not only more accurately due to their origin, they also promote an easier distinction of the reference surface used for future work and research in this area.

An important step for the future is to investigate how the structure of allotment gardens affects their cooling effect. For example, by a comparison of allotments with similar size but different plant cover. Allotment gardens from different countries (Speak et al., 2015) could provide some insight into which garden structure is most effective in locally reducing the UHI of a city by its cooling effect and when these effects occur, similar to the specific cooling patterns of urban parks (Spronken-Smith and Oke, 1998). On basis of the findings made so far by the literature research it can be strongly assumed that allotment gardens with many larger trees rather have the potential to be cooler during the day than their environment. In the case of a low tree cover, a local overheating is possible in the daytime compared to the urban environment, but such allotments should be able to cool the urban environment better at night. Variations in the usage of cultivated plants and grass surfaces could produce an allotment garden concept tailored to maximal improve the city climate. However, the previous degree of horticultural self-determination of the allotment holders has to be maintained, above all in order to maintain the knowledge of historical used plants and the garden culture.

A general proposal to increase the cooling effect of a small garden colony on the urban environment are few street trees or trees with high crown base in the border area of the colony to facilitate the creation of at most unhindered nightly interaction with the urban surrounding by an allotment breeze. It is also important that the colony is at least at street level, because at lower levels the cold air is accumulates within the green space (von Stülpnagel, 1987) what reduces its interaction with the built-up environment. To have a maximum nocturnal cooling and to irrigate the plants nevertheless sufficiently, an irrigation in the morning could make sense. This would increase colony evaporation in the first half of the day and would damp temperature rise on the ground (Spronken-Smith, 1994). At night, on the other hand, the meanwhile mostly dry soil surfaces with again lower heat storage capacity (Spronken-Smith and Oke, 1998, Bongardt, 2006) could promote the development of a stronger nightly ACI and an increased cooling effect of the colony.

9 Conclusion

The present study proved that the 6.5 ha wide colony Johannisberg on the southwest border of the city centre of Berlin has a significant nocturnal cooling effect on its surroundings, which – as assumed to the beginning of this work – is comparable in magnitude to that of urban parks. During radiation nights, the colony can be over 3 K colder than its urban surrounding and cools its urban adjacent urban neighbourhood in the second half of the night typically in a dimension of 1–2 K.

Therewith, the hypothesis of the existence of a significant inner-urban temperature depression produced by the surface characteristics of the allotment colony and namely introduced with the “Allotment Cool Island”, in short ACI in this work could be proven.

The work additionally proved that the colony forms during radiation nights an own microscale wind system, like already assumed by in second hypothesis of chapter 1. This even at all first time measured "allotment breeze" transports the cold air of the colony Johannisberg through the streets in its urban neighbourhood and cools therewith the residential area around the colony. Important is that this cooling interaction was measured in a night with minimum temperatures nearby 20°C in the inner-city parts of Berlin, that followed on a hot summer day with maximum temperatures above 31°C and therewith for a situation when the cooling is also actually important. Accordingly relevant is the cooling of the colony for its urban neighbourhood. The results of this work suggest a maximum range of cooling influence at the level of the investigated Homburger Straße section, ranging at least 160 m west and 80 m east of the colony. A noteworthy advection of cold air with the superordinated wind could not be detected.

A special feature of this work is that efforts were made to avoid an influence of other big green areas to represent only the effect of an allotment garden area itself. As a result, this work, which bases on more than one-month-lasting measurements should have a higher informative value about the cooling effect of the colony compared to the few older studies that were found. This point is important because some of the earlier studies underestimated the actual cooling potential of allotment areas remarkable.

In summary, the allotment garden colony Johannisberg turned out during the work as an important temperature-regulating green area in the border area of Berlins city centre, although it was considered to have no positive microclimatic influence on its surroundings. It is very likely that other allotment gardens of similar size near the inner-city area develop a similarly strong cooling effect under comparable conditions as in this work. In addition, it is very likely that the cooling effect of larger allotment areas is even higher, analogous to the PCI of parks.

With the "Allotment cool island" (ACI), the allotment gardens now have an easily quantifiable size, which clearly indicates the importance of these green areas in cities and strengthens allotment gardens in their right to exist. The nocturnal temperature reduction as Urban Ecosystem Service counteracts urban overheating due to the UHI phenomenon, thus promoting the health of the population, particularly in the overheated inner-city districts. The growing and aging population of Berlin makes this point very important, since exactly for these risk groups a low of air temperature can reduce the mortality rate. Against the background of the progressing housing construction in large cities like Berlin and the consequent described decline of allotment gardens in Berlin and Germany, this point is a particularly important aspect for the preservation of allotment gardens. Allotment gardeners and their associations can in the future rely on the positive microclimatic effect of their colonies. On the other hand, the investigated temperature-regulating function of allotments can and should increasingly be recognized and taken up by city planners and architects. Both points can counteract the progressive decline of allotment gardens and even increase the integration of allotments in the inner parts of the city. For example, by creating new garden colonies on newly created fallow land in the inner-city area instead of new parks or houses. This measure would not only be a sustainable solution for increased heat stress due to the UHI. It would also offer the socially disadvantaged part of the population a possibility for compensation and recreation. The inner-city areas of metropolis, which require allotments through the possibility of nature contact and balance most, would also most benefit from their cooling effect. The will for the management of allotments in the population exists. 14,000 people on the waiting lists for an allotment garden in Berlin (Bundesverband Deutscher Gartenfreunde e. V., 2016) prove this statement. When provided, the area would be used definitely.

Although the topic of microclimatic benefits of allotment gardens is not new, as assumed when starting this work, there was an urgent need for research, which includes long-term measurements and shows how relevant and worth research is in this area. This is certainly still expandable, for example, by a denser network of measurements of further colonies or by model simulations. There is still further research needed to compare the results of this work, for example, with allotment gardens of other sizes or in other cities. This work provides a current and important base for the knowledge of the microclimatic influence of allotment gardens in a large city in mid-latitudes. The results also show how important it is to preserve allotment gardens in big cities and to promote their existence. The rising global temperature, the increased incidence of heat waves superimposed by the urban heat island as well as the growth and aging of the population in cities like Berlin necessitate rapid, determined and consistent action in the sector of urban planning and urban development, which prevents the decline of allotments as quickly as possible and encourages their integration into the urban space in future.

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