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The Effects of Urban Heat Island in Phnom Penh: A Case Study of Khan Boeung Keng Kang and Khan Pou Senchey

SE Bunleng[1,2*], CHOI Daniel M.[2], CHHINH Nyda[3], HAHNE Janalisa[4], YAV Net[2], KUPSKI Sebastian[4], RANG Chandary[2], and KATZSCHNER Lutz[4]

[1]Faculty of Social Science and Humanities, Royal University of Phnom Penh (RUPP), Russia Federation Boulevard, Khan Toul Kork, Phnom Penh, Cambodia.
[2]Department of Geography and Land Management, Royal University of Phnom Penh (RUPP), Russia Federation Boulevard, Khan Toul Kork, Phnom Penh, Cambodia.
[3]Department of Economic Development, Royal University of Phnom Penh (RUPP), Russia Federation Boulevard, Khan Toul Kork, Phnom Penh, Cambodia.
[4]Institute for Climate and Energy Concepts (INKEK), Schillerstrasse 50, D-34253 Lohfelden, Germany.

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*Corresponding author: Faculty of Social Science and Humanities, Royal University of Phnom Penh (RUPP), Russia Federation Boulevard, Khan Toul Kork, Phnom Penh, Cambodia.
E-mail address: se.bunleng@rupp.edu.kh (S. Bunleng)
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សង្ខិត្តន័យ

រាជធានីភ្នំពេញនៃប្រទេសកម្ពុជាស្ថិតក្នុងចំណោមទីក្រុងនានាលើពិភពលោកដែលមានការរីកចម្រើនយ៉ាងឆាប់រហ័សបំផុតខាងផ្នែក កនគរូបនីយកម្ម និងសំណង់។ ការរីកចម្រើននេះកំពុងតែធ្វើឱ្យមានកំណើនឥទ្ធិពលនៃប៉ារ៉ាបូលកម្តៅក្នុងទីក្រុង។ ប៉ារ៉ាបូលកម្តៅនៅក្នុងតំបន់ទីក្រុងចេះតែកើនឡើងខ្ពស់ទៅៗជាងតំបន់ជនបទដោយសារមានការកើនឡើងនូវរូបធាតុស្រូបកម្តៅដូចជាកម្រាលបេតុង និងកម្រាលកៅស៊ូជាដើម។ ការសិក្សានេះបានវិភាគទិន្នន័យសីតុណ្ហភាពខ្យល់ល្បឿនខ្យល់បក់និងទិសដៅខ្យល់បក់នៅទីក្រុងភ្នំពេញក្នុងឆ្នាំ២០២១ដើម្បីអង្កេតពីឥទ្ធិពលនៃប៉ារ៉ាបូលកម្តៅ និងផលប៉ះពាល់ទៅលើផាសុខភាពរបស់មនុស្សក្នុងទីក្រុង។ ការស្រាវជ្រាវនេះបានបង្ហាញថា៖ ខណ្ឌបឹងកេងកងដែលជាមជ្ឈមណ្ឌលពាណិជ្ជកម្ម និងការងារមានអាំងតង់ស៊ីតេនៃប៉ារ៉ាបូលកម្តៅខ្ពស់ជាងនៅខណ្ឌពោធិ៍សែនជ័យដែលនៅជាយក្រុង ដោយសារខណ្ឌបឹងកេងកងមានសំណង់អាគារខ្ពស់ៗច្រើនជាងនិងមានចរន្តខ្យល់បក់ខ្សោយជាងនៅខណ្ឌពោធិ៍សែនជ័យ។ ការសិក្សានេះក៏បានបង្ហាញផងដែរថាអាំង តង់ស៊ីតេនៃប៉ារ៉ាបូលកម្តៅក្នុងទីក្រុងនារដូវប្រាំងមានសភាពក្តៅខ្លាំងជាងក្នុងរដូវវស្សាបាតុភូតនេះទំនងជាកើតឡើងដោយសារសំណើមបរិយាកាស មានកម្រិតទាបនៅរដូវប្រាំងដែលធ្វើឱ្យផ្ទៃដីស្រូបនិងស្តុកកម្តៅបានកាន់តែច្រើន។ កំណើនអាំងតង់ស៊ីតេនៃប៉ារ៉ាបូល កម្តៅក្នុងទីក្រុងភ្នំពេញ អាចបង្កភាពក្តៅស្អុះស្អាប់ខ្លាំង ជាពិសេសនៅពេលថ្ងៃ។ ភាពក្តៅស្អុះស្អាប់នេះអាចបង្កឱ្យមាន បញ្ហាសុខភាពមួយចំនួនដូចជា ការរមួលក្រពើ ការអស់កម្លាំងនិងជំងឺដាច់សរសៃឈាមខួរក្បាលជាដើម។ការសិក្សានេះបានសន្និដ្ឋានថាការចាត់វិធានការកាត់បន្ថយឥទ្ធិពលនៃប៉ារ៉ាបូលកម្តៅនៅទីក្រុងភ្នំពេញ និងនៅទីប្រជុំជននានា ដែលមានការលូតលាស់ឆាប់រហ័ស ខាងផ្នែក កនគរូបនីយកម្ម និងសំណង់ មានសារៈសំខាន់ខ្លាំងណាស់។ វិធានការ

ទាំងនោះអាចមានដូចជា ការបង្កើនទីវាលបៃតង ការប្រើសម្ភារសំណង់ដែលមានពណ៌ភ្លឺថ្លា និងការជំរុញជម្រើសដឹកជញ្ជូនប្រកបដោយចីរភាពជាដើម។ លទ្ធផលនៃការសិក្សានេះអាចលើកកម្ពស់ការយល់ដឹងបន្ថែមទៀតអំពីឥទ្ធិពលនៃប៉ារ៉ាបូលកម្ដៅក្នុងទីក្រុង និងការអនុវត្តវិធានការសម្របក្នុងការកាត់បន្ថយនិងបន្សាំទៅនឹងប៉ារ៉ាបូលកម្ដៅនៅក្នុងទីក្រុង៕

Abstract

Phnom Penh, Cambodia, is one of the most rapidly urbanizing cities in the world, and this urbanization is driving an increase in the urban heat island (UHI) effect. The UHI effect is the experience of urban areas getting higher temperatures than rural areas due to the concentration of heat-absorbing materials such as concrete and asphalt. This study analyzed air temperature, wind speed and direction data from Phnom Penh in 2021 to investigate the UHI effect and its impact on human thermal discomfort. The study found that the UHI intensity is stronger in the central business district (CBD) of Khan Boeung Keng Kang than in the suburban district of Khan Pou Senchey. This is likely due to the higher built-up area and lower wind speed in Khan Boeung Keng Kang. The study also found that the UHI intensity is stronger during the dry season than during the wet season. This is likely due to the lower humidity during the dry season, which allows surfaces to absorb and retain more heat. The increased UHI intensity in Phnom Penh can create significant human thermal discomfort, especially during the daytime. This discomfort can lead to a variety of health problems, including heat cramps, heat exhaustion, and heat stroke. The study concludes that it is important to take steps to mitigate the UHI effect in Phnom Penh and other rapidly urbanizing cities. This could include measures such as increasing green space, using lighter-colored building materials, and promoting sustainable transportation options. The results of this study can enhance more understanding of the UHI effects and have practical implications on the appropriate UHI-related mitigation and adaptation measures.

1. Introduction

Urban heat island (UHI) is the temperature in an urbanized area that is hotter than its surrounding rural areas (Howard, 1833; Li et al., 2011; Oke, 1982; Yuan & Bauer, 2007). The urbanized areas typically have darker surfaces and less vegetation distribution than surrounding suburban or rural areas that generally have higher capacity to absorb more incoming solar radiation leading to the UHI phenomenon (Kaloustian & Diab, 2015). Anthropogenic heat release (Rizwan et al., 2008) and traffic jams of transportation networks (Qiao et al., 2014) are also the sources of the UHI phenomenon in the city.

The UHI is regarded as one of the main concerns caused by urbanization (Lu et al., 2015; Makinde & Agbor, 2019; Rizwan et al., 2008). The UHI is strongly correlated with the urbanization factors including population (Atkinson, 2003; IPCC, 2007; Landsberg, 1981; Oke, 1973), economy (Gusso et al., 2015; Jones et al., 1990), city size (Atkinson, 2003; IPCC, 2007; Landsberg, 1981; Oke, 1973), geometric characteristics (Gusso et al., 2015; Jones et al., 1990) and buildings (Atkinson, 2003; IPCC, 2007; Landsberg, 1981; Oke, 1973). The UHI causes issues such as increased energy consumption (Lee et al., 2019; Qiao et al., 2014), changes in relative humidity (K. Lee et al., 2019) and human thermal stress (Lee et al., 2019; Waibel et al., 2020).

The UHI phenomenon is strongly correlated with urbanization growth of darker surface area (Li et al., 2009; Lu et al., 2015), the increase in air temperature (Cui & Shi, 2012), and the constant increase of buildings and paved roads (Zhao et al., 2016). The increased UHI intensity occurs in the city centers influenced by urban structures (Son et al., 2017), land use and land cover change (Doan et al., 2019), and the increased built-up areas (Nguyen, 2020).

The main causes of urbanization are the growth of the urban population (Delazeri et al., 2021; Li et al., 2018; Tacoli et al., 2015; Zhao et al., 2016), infrastructural development (Halder et al., 2021) and economic activities (Halder et al., 2021). Urbanized areas are still attractive places for more people to work and live, leading to more anthropogenic activities and urban expansion (Akbari & Kolokotsa, 2016; Kaloustian & Diab, 2015; Mirzaei, 2015). More people in the world today live in urban areas than in rural areas, with 30% of people in the world living in urban areas in 1950, which increased to 55% in 2018 (UNDESA, 2019) and continued to increase to 68% by 2050 according to urban population projections (UNDESA, 2019).

Urbanization usually changes the structure, properties and spatial distribution of the urban surface dramatically, particularly the decreased green space (Ma et al., 2010) and altered albedo and geometry (Oke, 1982). Urbanization development has transformed the natural landscape into impervious surfaces such as housing developments, paved roads, infrastructure, buildings, and parking lots with water-resistant materials such as asphalt, concrete, brick, and stone (Hua et al., 2020; Makinde & Agbor, 2019; Oke, 1982; Vujovic et al., 2021;

Wu et al., 2014), and these changes influence urban-rural differences of surface radiance and air temperature (Weng, 2003).

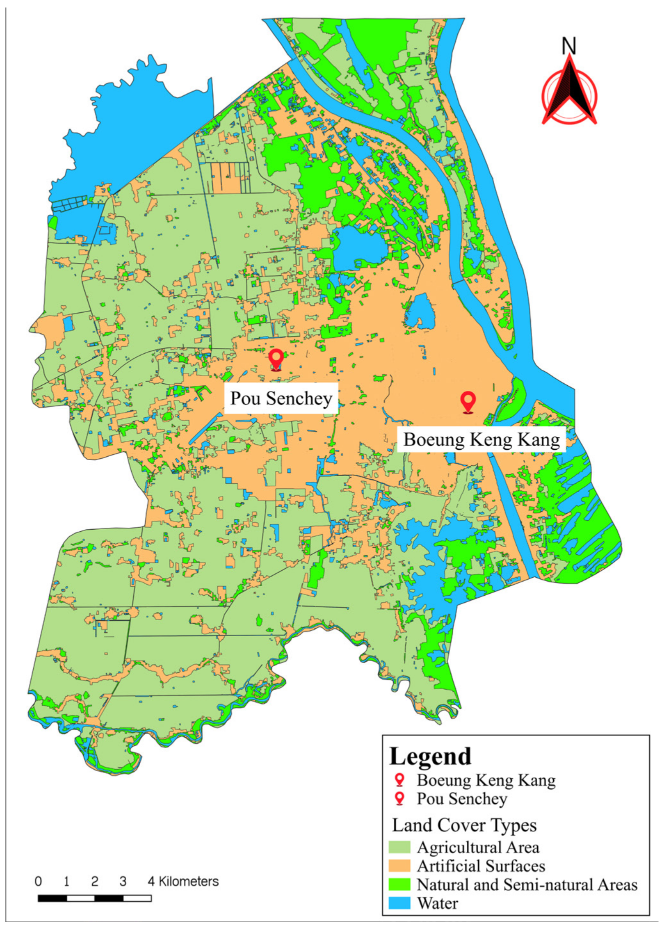
One of the biggest challenges that humans is facing is to adapt urban areas to the combined effects of urban heating (Georgescu et al., 2014; Li et al., 2018; Parker, 2004; Patz et al., 2005; Sun et al., 2016) and global warming (Georgescu et al., 2014; Parker, 2004; Patz et al., 2005; Sun et al., 2016). The combination of increasing urban population growth to 68% by 2050 (UNDESA, 2019) and an unprecedented rate of global climate change (IPCC, 2014; Parker, 2004; Qin, 2014; Sun et al., 2016) make urban areas increasingly and dramatically changed to become impervious surfaces (Lee & Kim, 2016). Therefore, it is necessary to take urgent action to create appropriate urban design and planning with nature-based solutions to mitigate the UHI intensity to enhance urban quality of life.

In recent years, Phnom Penh is experiencing rapid urbanization. The urban area has increased from 40 km^2 in 1990 (Mialhe et al., 2019) to 678.47 km^2 in 2017 (NCSD et al., 2018). The majority of urban areas become impervious in the various underlying surfaces. Land use/land cover of Phnom Penh city has been changed by converting agricultural, natural and semi-natural areas to artificial ones (Fig. 1 & Fig. 2). About two-thirds of the total areas of the city in 2003 was mostly agricultural areas (Fig. 1). About one-third of the total areas was artificial surfaces in 2003 (Fig. 1), while about two-thirds of the city in 2017 was artificial surfaces (Fig. 2).

Rapid urbanization development through the expansion of built-up areas, the growth of the ubran population and economic activities in the city plays a significant role in determining its effect on the variation of the temperature (Chen et al., 2006; Oke, 2009) and the UHI intensity in Phnom Penh. The rapid growth of high-rise buildings in Phnom Penh creates a complicated urban geometry that traps more energy and changes urban ventilation, increasing the amount of solar radiation to heat the urban surface and air temperature in the city scale. The increased UHI intensity poses human health problems, especially thermal discomfort for urban people in Phnom Penh city.

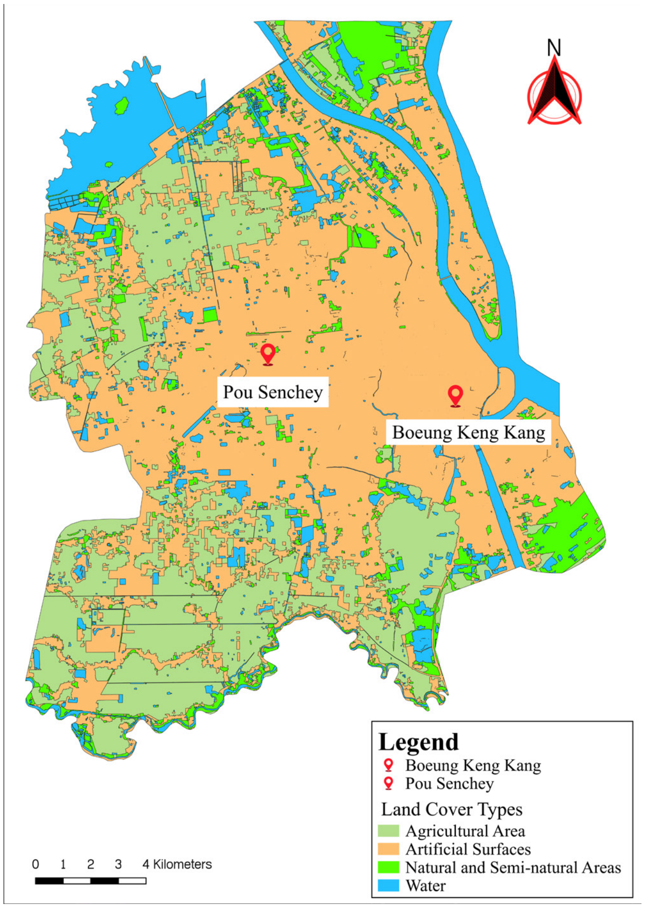
The morphology of Phnom Penh, such as the urban design shape, roads, and land use, has been changed daily to become impervious-surface and building dominant (Fig. 1 & Fig. 2) with high-rise buildings and narrow street canyons which reduce incoming ventilation, leading to an increased UHI intensity at the city. The central business districts (CBDs) with high, dense buildings can reduce urban ventilation, which is one of the significant causes of the UHI phenomenon in Phnom Penh. Observations from the temperature analysis indicate that higher temperatures occur in the CBDs, i.e., Khan Boeung Keng Kang, because high, dense buildings block inflowing winds, whereas low temperatures occur in suburban areas, i.e., Khan Pou Senchey, which is an area that is structurally less developed with more open and wider spaces, allowing inflowing winds to pass through, leading to reduce the UHI intensity.

The building sector in Phnom Penh has been very dynamic over the last decades and it is necessary to consider the urban climate characteristics. Therefore, in city planning, the urban climate and the increased heat island effect are important issues with respect to energy use, human well-being, and thermal comfort. Urban climatic analyses can provide information to help mitigate and adapt to such issues. Therefore, information on the intensity of the UHI in Phnom Penh is essential for developing effective urban climate design and planning strategies to mitigate its impacts. Phnom Penh is the most rapidly urbanizing city in the country. Therefore, Phnom Penh was selected as a case study to investigate the daily and seasonal evolution of the UHI. The aims of this study are (1) to identify the daily and seasonal variations of the UHI intensity and impacts of ventilation



Source: World Bank, n.d)

Fig. 1: Land use/land cover change of Phnom Penh in 2003 and location of the meteorological stations.



Source: World Bank, n.d

Fig. 2: Land use/land cover change of Phnom Penh in 2017 and location of the meteorological stations.

on the UHI intensity (2) to analyze the influence of the UHI intensity on human thermal discomfort.

2. Study Areas and Research Methods

Phnom Penh is located in the contiguous zone of four rivers: Tonle Sap, Tonle Bassac, Upper Mekong, and Lower Mekong (Olson & Morton, 2018). Phnom Penh has a typical monsoonal climate with an annual average rainfall amount of 1261 mm and an annual average temperature of 28.25°C (RIMES & UNDP, 2020). Urbanization development has changed the landscape of Phnom Penh city from pervious to impervious areas (Babel et al., 2021) that may absorb more solar radiation during daytime. Phnom Penh capital was selected as a study site because this city has a high population density of 14.7% (NIS, 2019) and is more urbanized than other cities in Cambodia (NIS, 2019; WBG, 2017). Phnom Penh's capital is also serving as the central business center of the country. It is also the country's largest and fastest-growing city (WBG, 2017).

In Phnom Penh, two areas, Khan Boeung Keng Kang and Khan Pou Senchey, were chosen for this study due to their different stages of development and city density and structure. Khan Boeung Keng Kang is in the central business district (CBD) and is considered an urbanized area. Its total population is 66,658, with a total area of 4.1 km^2 (NIS, 2019). The population density of Khan Boeung Keng Kang is 16,258 people per km^2. With high population density, high-rise buildings appear to be exposed to direct solar radiation that can cause increased UHI intensity behind the buildings (Banerjee et al., 2022; Nugroho et al., 2022).

Khan Pou Senchey is in the suburban district and is considered less developed. Its total population is 226,871 people, with a total area of 60.6 km^2 (NIS, 2019). The population density of Khan Pou Senchey is 3,745 people per km^2. Low-rise buildings with low population density and broad neighborhoods can mitigate the UHI intensity in Khan Pou Senchey as the result of wind flow passing through it.

Two automatic weather stations (AWSs) were installed in two different locations in Phnom Penh: Khan Boeung Keng Kang and Khan Pou Senchey (Fig. 1 & Fig. 2). Khan Boeung Keng Kang with its coordinates of 104.925365, 11.548953 represents the urbanized area and Khan Pou Senchey with its coordinates of 104.862817, 11.562036 is regarded as the suburban area, respectively (Fig. 1 & Fig. 2). The stations were installed on the rooftop of the buildings to measure necessary weather parameters such as air temperature and ventilation at a 15-minute interval continuously for a period of 1st January to 31st December 2021. A 15-minute data record of air temperature and wind speed and direction was aggregated on daily basis to calculate and analyze daily and seasonal variations of the UHI intensity and wind speed and direction. The sensors of temperature, wind speed and direction in the set of the professional wideband code division multiple access (WCDMA)/global system for mobile communication (GSM) weather station were installed (Fig. 3) and sensors technical data are shown in (Table 1).

The air temperature difference between Khan Boeung Keng Kang and its surrounding Khan Pou Senchey has been analyzed to demonstrate the UHI intensity. Analyzing the UHI intensity within daytime and nighttime in different days and seasons in Khan Boeung Keng Kang and Khan Pou Senchey is necessary. The air temperature variations of Khan Boeung Keng Kang and Khan Pou Senchey on the scale of the day were calculated. The UHI intensity was calculated using AWS air temperature in the urban area minus the air temperature in suburban areas (Oke, 1973), in which the equation is written as follows:

Table 1: Sensors technical data.

Measurement	*Range*	*Resolution*
Temperature	-40-+60°C	0.1°C
Wind speed	0-50 m.s-1	
Wind direction	0-359°	

Fig. 3: Professional WCDMA/GSM weather station.

$$UHI = T_{Urban} - T_{Suburban} \quad (1)$$

Thus,

$$UHI = T_{Khan\ Boeung\ Keng\ Kang} - T_{Khan\ Pou\ Senchey} \quad (2)$$

Daytime and nighttime UHI intensity (UHII) in the dry season (November-April) and wet season (May-October) were averaged to examine daily and seasonal variations of the UHI. The daily variation of the UHI (DVUHI) and the seasonal variation of the UHI during daytime ($SVUHI_{day}$) and during nighttime ($SVUHI_{night}$) were defined as the daily range of the UHI and the wet and dry range of the UHI (Sun et al., 2019), in which the equations are written as follows:

$$DVUHI = UHII_{day} - UHII_{night} \quad (3)$$

$$SVUHI_{day} = UHII_{day}^{dry} - UHII_{day}^{wet} \quad (4)$$

$$SVUHI_{night} = UHII_{night}^{dry} - UHII_{night}^{wet} \quad (5)$$

To demonstrate the effect on mitigating the UHI intensity, ventilation between Khan Boeung Keng Kang and Khan Pou Senchey has been analyzed. Daily wind speed and direction data of both Khan Boeung Keng Kang and Khan Pou Senchey in the observation locations obtained were utilized to analyze the characteristics of ventilation within the city. The seasonal wind rose graphs were plotted to determine the most likely directions of wind flow in the study areas. Then, the correlation between the UHI intensity and wind speed was analyzed to determine ventilation's impact on the intensity in the observation areas.

3. Results and Discussions

2.1 Air temperature difference caused by urban development, density and structure

Air temperature in the city scale is different from one location to another due to impervious surface, urbanization development stages, distance to water bodies, vegetation density, and distance to CBDs (Chen et al., 2018; Kloog et al., 2012; Oswald et al., 2012; Schatz & Kucharik, 2014; Shi et al., 2018; Shi et al., 2019). Land use change in Phnom Penh city, particularly urbanization development intensity, vegetation cover, and the decreased water body increase air temperature through energy stored on the urban surface and energy released from human-induced heat. The analysis of air temperature showed that the mean air temperature is higher in Khan Boeung Keng Kang than in Khan Pou Senchey in 2021 because Khan Boeung Keng Kang is the city center with high-rise buildings and narrow neighborhoods that wind flow cannot pass through in order to cold down the air temperature in the city center. The maximum and minimum air temperatures in Khan Boeung Keng Kang are 34.1 and 22.8°C, while those in Khan Pou Senchey are 32.5 and 22.0°C. Hence, the average air temperature of Khan Boeung Keng Kang and Khan Pou Senchey is 29.0 and 28.6°C in 2021 (Fig. 4). This indicates that the urbanized area is warmer than the suburban area of Phnom Penh city. According to Cao et al. (2021), the air temperature is higher in dense built-up areas than in suburban areas with open and green space. This demonstrates that air temperature in the urbanized areas is higher than that in suburban areas.

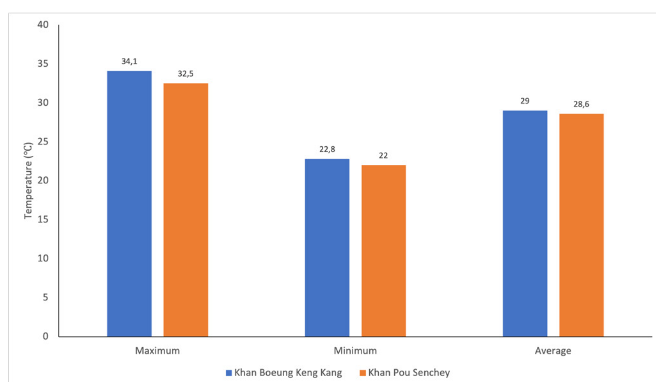


Fig. 4: The air temperature in the study Khans.

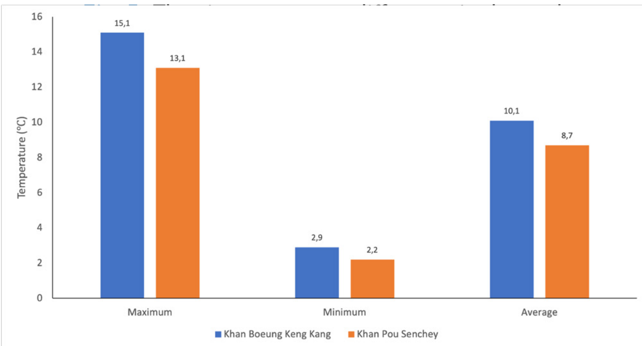


Fig. 5: The air temperature difference in the study Khans.

The characteristics of air temperature difference are based on whether it is urbanized areas or suburban areas. Air temperature difference was calculated by average urban air temperature minus suburban air temperature. The result shows that the average air temperature differences in Khan Boeung Keng Kang and Khan Pou Senchey are 10.1 and 8.7°C. The average maximum air temperature difference in Khan Boeung Keng Kang is 15.1°C while that in Khan Pou Senchey is 13.1°C. The average minimum air temperature difference in Khan Boeung Keng Kang is 2.9°C while that in Khan Pou Senchey is 2.2°C. Hence, the higher temperature occurred in Khan Boeung Keng Kang while the lower temperature occurred in Khan Pou Senchey (Fig. 5). Mughal et al. (2020) and Ng (2015) also found that temperatures are higher in the urban center and lower in suburban areas in Singapore. According to Nichol et al. (2014), the temperature in Hong Kong is higher in urbanized areas than in suburban areas. The high temperature appeared in Khan Boeung Keng Kang because Khan Boeung Keng Kang is dominated by dense buildings, narrow neighborhood and street canyons. Wind in Khan Boeung Keng Kang has low capacity to bring the heat load out from the city center due to low wind speed. Hence, temperature is higher in the urbanized area than in the suburban area of Phnom Penh city.

2.2 Daily variation of the UHI intensity during daytime and nighttime

The data observed from the AWSs in 2021 is used to study the daily variation of the UHI intensity. Analysis of DVUHI intensity showed that the temperature difference during daytime is stronger than that during nighttime in both observation locations. The average temperature difference in Khan Boeung Keng Kang and Khan Pou Senchey during daytime is 9.8 and 8.3°C, while that in Khan Boeung Keng Kang and Khan Pou Senchey during nighttime is 4.7 and 4.7°C (Fig. 6 & Fig. 7). The DVUHI intensity is higher in Khan Boeung Keng Kang than that in Khan Pou Senchey because ventilation characteristics in Khan Boeung Keng Kang is unable to play its role to mitigate the temperature due to its wind velocity. The

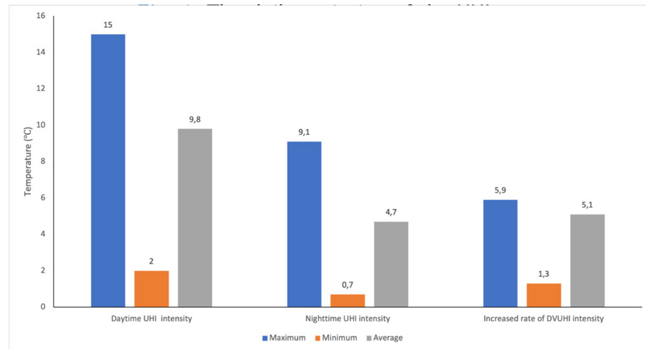


Fig. 6: The daily variation of the UHI intensity in Khan Boeung Keng Kang.

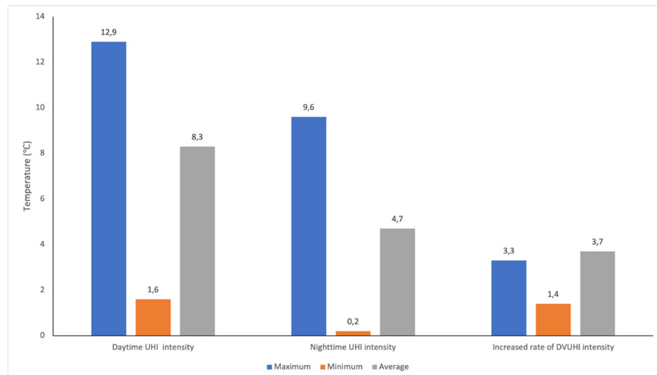


Fig. 7: The daily variation of the UHI intensity in Khan Pou Senchey.

increased rate of the DVUHI intensity between daytime and nighttime in Khan Boeung Keng Kang and Khan Pou Senchey is 5.1 and 3.7°C (Fig. 6 & Fig. 7) because of a higher number of DVUHI intensity in Khan Boeung Keng Kang than that in Khan Pou Senchey. This revealed that the DVUHI intensity in Khan Boeung Keng Kang is stronger than that in Khan Pou Senchey. The study of Sun et al. (2019) at the Yangtze Delta in China also confirmed that the DVUHI intensity occurred in urban rather than suburban areas.

Furthermore, the characteristics of the DVUHI intensity differ between dry and wet seasons. The maximum and minimum DVUHI intensity between daytime and nighttime in the dry season are 4.2 and -0.7°C, while those in the wet season are 7.2 and -5.3°C. Hence, the average DVUHI intensity is strong in the dry season (1.6°C) and weak in the wet season (1.2°C). Therefore, this study confirmed that the DVUHI intensity is the most apparent in the dry season in Phnom Penh city because there is low humidity in the air that cannot reduce the high temperature in the dry season.

Two typical days of dry season and the other two days of wet season were selected based on the observation experiment data and comprehensive comparison to observe the characteristics of hourly variations of the UHI intensity (Fig. 8). In 16th June and 28th September of the dry season are considered the early and the late wet seasons, while 28th December and 16th March are

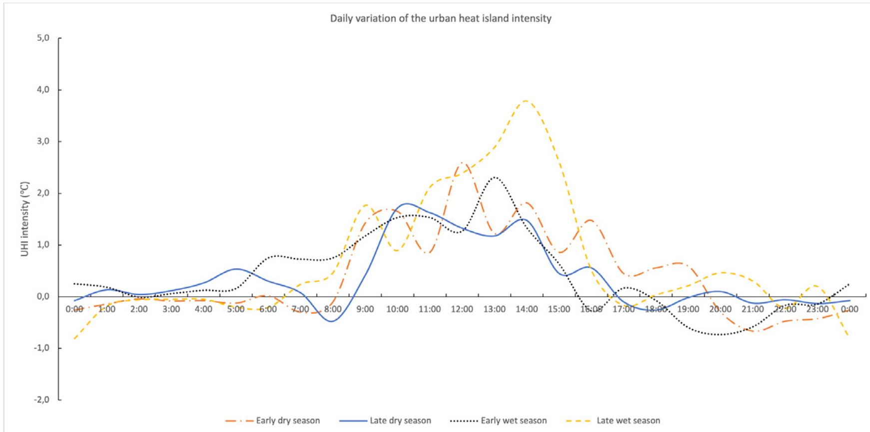


Fig. 8: Daily variation of the UHI intensity of selected days in dry and wet seasons of the study Khans.

considered the early and late dry seasons. The result shows that the UHI intensity is strong during daytime and weak during nighttime (Fig. 8). Temperature difference between Khan Boeung Keng Kang and Khan Pou Senchey is small at nighttime, and cold island effect occurs on some occasions. This means that the temperature in Khan Boeung Keng Kang is lower than that in Khan Pou Senchey (Fig. 8). Gaffin et al. (2008) also found that hourly UHI phenomenon occurred in some locations of New York city, USA. According to Yang et al. (2019), the hourly UHI phenomenon appeared in Changchun city of Jilin Province, China. Hourly temperature variations were higher in the urbanized area than those in the rural areas which occurred during 14:00 (Yang et al., 2019). This study confirms that the higher UHI intensity appeared during daytime around 14:00 (Fig. 8). With the disappearance of solar radiation at nighttime, the low temperature can be observed. A temperature increase has been observed during the daytime, particularly in the afternoon, with the increase of the solar elevation angle and urban structures such as buildings, paved roads, and parking loads. For Khan Boeung Keng Kang, a significant heat load is stored in the underlying surface and buildings during daytime, leading to a higher temperature than Khan Pou Senchey. Therefore, a typical hourly UHI phenomenon appears.

2.3 Seasonal variation of the UHI intensity in dry and wet seasons

There are no significantly identifiable patterns in the UHI (SVUHI) seasonal variation. The UHI intensity is different in both dry and wet seasons. The SVUHI intensity during daytime and nighttime in different seasons was analyzed. The result shows that the average SVUHI intensity during daytime in dry and wet seasons is 1.6 and 1.3°C while that during nighttime in dry and wet seasons is -0.1 and 0.1°C (Fig. 9). This revealed that the SVUHI intensity occurred stronger during daytime than during nighttime for both dry and wet seasons. The SVUHI intensity is stronger in the dry season and weaker in wet season during the daytime, but nighttime SVUHI intensity in dry season is weaker and stronger in wet season. Hence, the daytime UHI intensity is 0.3°C. The nighttime UHI intensity is -0.2°C), the cold island effect. The study of Sun et al. (2019) at the Yangtze Delta, China, also found that the average SVUHI intensity is 1.38°C during daytime, which is higher than of 0.74°C during nighttime. The UHI intensity during daytime was higher than that during nighttime in wet season (Sun et al., 2019). Du et al. (2016) also found that the UHI intensity during daytime is 0.98°C and that during nighttime is 0.50°C. According to Peng et al. (2012), the average annual UHI intensity during daytime (1.5 ±1.2°C) was higher than that during nighttime (1.1 ± 0.5°C) with p-*value* < 0.001. This study also observed that the daytime UHI intensity is higher than nighttime UHI intensity in the study area of Phnom Penh city because urban areas have been covered by impervious surfaces that absorbed and stored thermal radiation during daytime. Daytime SVUHI intensity in dry season is hotter than dry season because relative humidity in dry season is very low, which cannot mitigate the UHI intensity during the daytime. With high relative humidity in wet season, daytime SVUHI intensity is much lower than that in dry

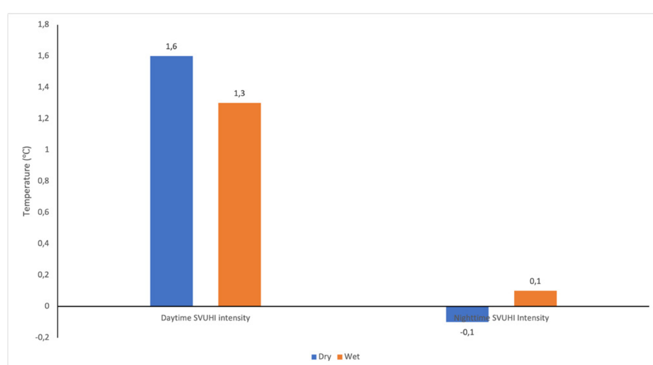


Fig. 9: The average daytime and nighttime SVUHI intensity in dry and wet seasons.

season. The nighttime SVUHI intensity is a cold island effect in dry season because it was influenced by cold wind from the Northeastern direction to reduce the heat effect during nighttime. In wet season, the UHI intensity was reduced due to occasional rainfall during nighttime. Therefore, the UHI intensity was observed to be lower during nighttime than during daytime.

2.4 Characteristics of wind speed and direction and their impacts of the UHI

Wind speed and direction were observed and analyzed over two seasons of 2021. The maximum wind speed in Khan Boeung Keng Kang in dry and wet seasons are 2.9 and 2.9 $m.s^{-1}$ while those in Khan Pou Senchey are 5.5 and 7.8 $m.s^{-1}$. The minimum wind speed in Khan Boeung Keng Kang in dry and wet seasons are 0.6 $m.s^{-1}$ and 0.4 $m.s^{-1}$ while those in Khan Pou Senchey are 1.3 and 1.4 $m.s^{-1}$. The average wind speed in Khan Boeung Keng Kang in dry and wet seasons are 1.4 and 1.3 $m.s^{-1}$ while those in Khan Pou Senchey are 3.1 and 3.1 $m.s^{-1}$.

The UHI intensity has been mitigated by ventilation. The high, dense buildings in Khan Boeung Keng Kang may reduce inflowing winds, leading to the increased UHI intensity in the study areas. Most of the wind flow in Khan Boeung Keng Kang during dry season is from the East, the Southeast and the Northeast (Fig. 10a) while that during wet season is from the East and the Northeast (Fig. 10b). The different colors of each spoke indicate the wind speed in meter per second ($m.s^{-1}$). The longest spoke shows the wind flows from the Southeast at speeds between 0.6 to 1.1 $m.s^{-1}$ (dark blue), 1.1 to 1.5 $m.s^{-1}$ (light-dark blue), 1.5 to 2.0 $m.s^{-1}$ (dark green), 2.0 to 2.4 $m.s^{-1}$ (green) and more than 2.9 $m.s^{-1}$ (yellow). The longer spoke shows the wind flows from the East at speeds between 0.6 to 1.1 $m.s^{-1}$ (dark blue), 1.1 to 1.5 $m.s^{-1}$ (light-dark blue), 1.5 to 2.0 $m.s^{-1}$ (dark green) and 2.0 to 2.4 $m.s^{-1}$ (green) (Fig. 10a). The wind mostly flows from the Northeast shown as the longest spoke at speeds between 0.4 to 0.9 $m.s^{-1}$ (dark blue), 0.9 to 1.4 $m.s^{-1}$ (light-dark blue), 1.4 to 1.9 $m.s^{-1}$ (dark green), 1.9 to 2.4 $m.s^{-1}$ (green), and more than 2.9 $m.s^{-1}$ (yellow) (Fig. 10b).

The characteristics of wind flow in Khan Pou Senchey during dry season are mostly from the East, the Southeast and the Northeast (Fig. 10c), while that during the wet season is from the Southeast, the South and the Southwest (Fig. 10d). The longest spoke shows that the wind flew from the Northeast during dry season at speeds between 2.1 to 3.0 $m.s^{-1}$ (light-dark blue), 3.0 to 3.8 $m.s^{-1}$ (dark green), 3.8 to 4.7 $m.s^{-1}$ (green), and 4.7 to 5.5 $m.s^{-1}$ (light green) (Fig. 10c). The longest spoke shows that the wind flew from the Southeast during wet season at speeds between 1.4 to 2.7 $m.s^{-1}$ (dark blue), 2.7 to 4.0 $m.s^{-1}$ (light-dark blue), 4.0 to 5.2 $m.s^{-1}$ (dark green), and 5.2 to 6.5 $m.s^{-1}$ (green) (Fig. 10d). wind flows in Khan Boeung Keng Kang and Khan Pou Senchey during dry season are almost the same, while those during wet season come from different directions. Different wind directions of both Khan Boeung Keng Kang and Khan Pou Senchey depend on the urban structure, urbanization development and also seasonal wind direction over Cambodia during dry and wet seasons. High-rise buildings and narrow neighborhoods in Khan Boeung Keng Kang have blocked incoming wind that cannot transport the heat load from the city center to the outer city center, such as Khan Pou Senchey. Hence, the UHI intensity in Khan Boeung Keng Kang becomes higher than that in Khan Pou Senchey

Urbanization development has influenced the characteristics of air temperature and wind speed in both Khan Boeung Keng Kang and Khan Pou Senchey. The lower wind speed in Khan Boeung Keng Kang has a lower capacity to transport the heat load from Khan Boeung Keng Kang to the outer city center, so the air temperature difference in Khan Boeung Keng Kang is relatively higher than Khan Pou Senchey. High-rise buildings and dense neighborhoods make the sky visibility factors of Khan Boeung Keng Kang narrow, leading to reduced urban ventilation in the area. This can increase the UHI intensity in Khan Boeung Keng Kang. Low-rise area and broad neighborhoods make wind flow pass through it. This can mitigate the UHI intensity in Khan Pou Senchey. The characteristics of wind speed in Khan Pou Senchey are higher than that in Khan Boeung Keng Kang; therefore, air temperature difference is lower in Khan Pou Senchey than in Khan Boeung Keng Kang. The UHI intensity is weaker when the wind speed is greater (Rajagopalan et al., 2014).

As shown in Fig. 11, the UHI intensity and average wind speed are negatively correlated. The UHI intensity during daytime and nighttime is significantly correlated with the average wind speed in both Khan Boeung Keng Kang and Khan Pou Senchey. In Khan Boeung Keng Kang, the UHI intensity during daytime has a significant negative correlation with the average wind speed in dry season ($R = -0.31$, $p < 0.001$) and wet season ($R = -0.15$, $p < 0.001$). The UHI intensity during nighttime similarly has a negative correlation with average wind speed in dry season ($R = -0.32$, $p < 0.001$) and wet season ($R = -0.29$, $p < 0.001$) (Fig. 11a & Fig. 11b). The wind speed is higher during daytime than during nighttime in Khan Boeung Keng Kang where the maximum wind speed in dry season is 2.9 $m.s^{-1}$ during daytime and 1.8 $m.s^{-1}$ during nighttime, respectively while that in wet season is 2.9 $m.s^{-1}$ during daytime and 1.9 $m.s^{-1}$ during nighttime. Similarly in Khan Pou Senchey, the UHI intensity during daytime has a significant negative correlation with the average wind speed in dry season ($R = -0.42$, $p < 0.001$) and wet season ($R = -0.12$, $p < 0.001$). The UHI intensity during nighttime has a negative correlation with average wind speed in dry season ($R = -0.30$, $p < 0.001$) and wet

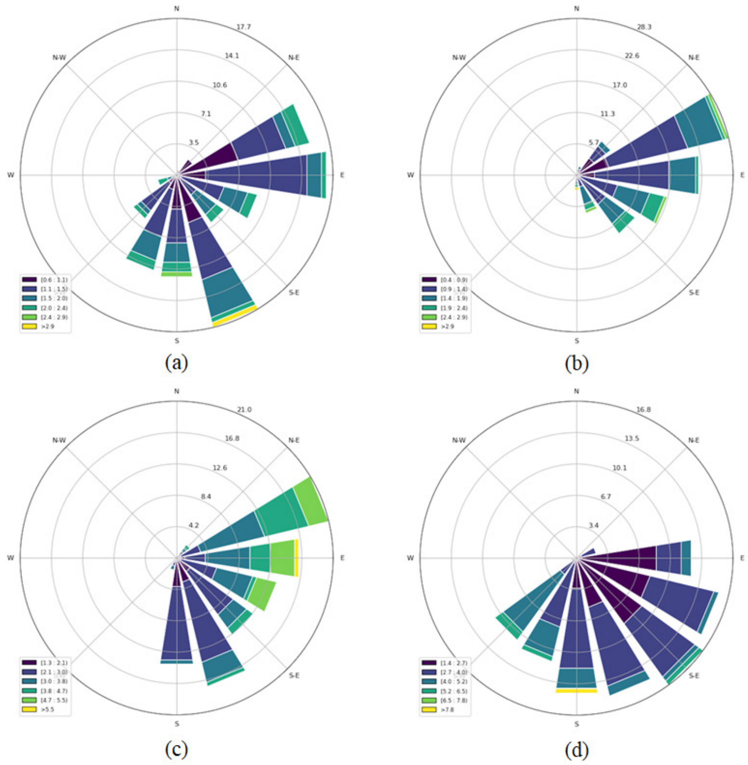


Fig. 10: The different colors of each spoke indicate the wind speed ($m.s^{-1}$). Wind rose diagram in Khan Boeung Keng Kang during a) dry season and b) wet season, and in Khan Pou Senchey during c) dry season and d) wet season.

season (R = -0.22, p < 0.001) (Fig. 11c & Fig. 11d). The wind speed is higher during daytime than during nighttime in Khan Pou Senchey where the maximum wind speed in the dry season is 5.5 $m.s^{-1}$ during daytime and 4.4 $m.s^{-1}$ during nighttime, respectively while that in wet season is 7.8 $m.s^{-1}$ during daytime and 5.5 $m.s^{-1}$ during nighttime. Urban street canyons mainly transport heat load from the city center to the outer city due to the blowing wind and dissipating long-wave radiation during nighttime (Chen et al., 2020; Du et al., 2016; Liu et al., 2020). Therefore, we have slower wind speeds during nighttime.

Overall, the correlations between the UHI intensity and average wind speed are most significant in the dry season and followed by the wet season (Fig. 11). Wind speed can potentially mitigate the UHI intensity in Khan Pou Senchey better than in Khan Boeung Keng Kang. Du et al. (2016) also found that the higher wind speed during spring and winter in the Yangtze River Delta Urban Agglomeration plays an important role in mitigating the city's UHI intensity. According to Yow (2007), wind significantly mitigates the UHI intensity in Orlando, Florida, USA. Also, Park (1986) found that the higher wind speed reduced the UHI effects in Seoul city, South Korea. Erell et al. (2011) also found that wind speed of 1 to 1.5 $m.s^{-1}$ reduced the temperature by 2°C in Singapore. Therefore, wind speed plays a significant role to be responsible for the UHI intensity in Khan Pou Senchey being lower than that in Khan Boeung Keng Kang.

2.5 Impacts of the UHI on human thermal comfort

Human thermal comfort has been affected by the UHI intensity during daytime hours (Qaid et al., 2016; Wu et al., 2014) . To understand the perceptions of local people in Phnom Penh, the household survey was conducted in 2023 with 100 households in Khan Boeung Keng Kang and 100 households in Khan Sen Sok in Phnom Penh city. Khan Sen Sok is a Khan which is located at the North of Khan Pou Senchey. It shares a border with Khan Pou Senchey. It was selected for the survey as it is easier to communicate and have connections with local people than Khan Pou Senchey. Four domains of thermal comfort, including sleeping, daily travel, work, and exercise, were analyzed. This is a preliminary study to understand the UHI effects on human thermal comfort of urban people. The result of this study is a good indication for further future research focusing on the impacts of the UHI on human health, in particular human thermal discomfort and urban heat stress.

Human thermal comfort is closely relevant to the influence of the UHI intensity. The UHI intensity is stronger during the daytime and weaker during nighttime (Fig. 12). The UHI intensity creates human thermal discomfort for the daily activities of urban people, particularly during the daytime. According to the survey, the category 'almost every day' was reported by 17%

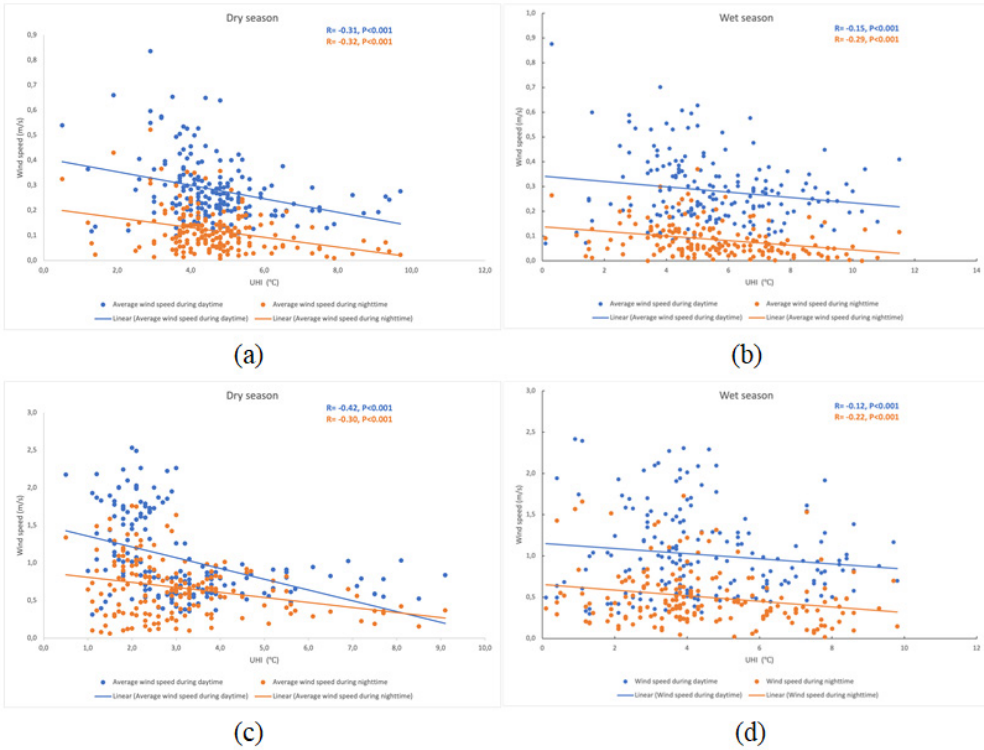


Fig. 11: Correlations between the UHI intensity and average wind speed at Khan Boeung Keng Kang (a & b) and Khan Pou Senchey (c & d).

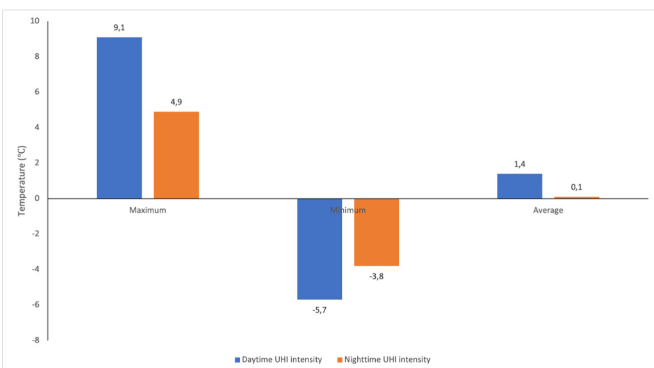


Fig. 12: The average daytime and nighttime SVUHI intensity in dry and wet seasons of Khan Boeung Keng Kang and Khan Pou Senchey.

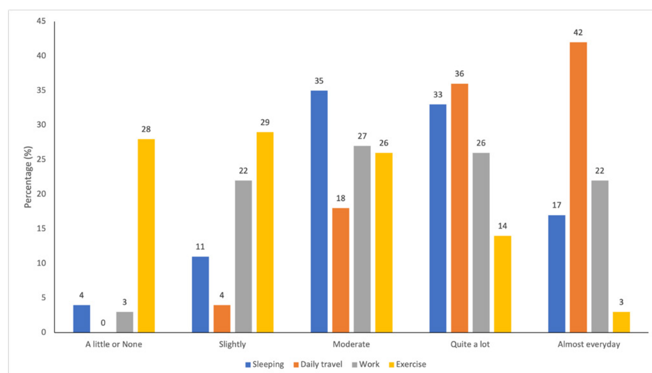


Fig. 13: Perceived urban heat stress of daily activities among surveyed respondents in percentage (%) in Khan Boeung Keng Kang.

for sleeping, 42% for daily travel, 22% for work, and 3% for exercise in Khan Boeung Keng Kang (Fig. 13) and 11% for sleeping, 51% for daily travel, 10% for work and 4% for exercise in Khan Sen Sok (Fig. 14). Based on the result, people living in Khan Sen Sok have experienced with higher thermal discomfort in Khan Sen Sok (51%) than in Khan Boeung Keng Kang (42%) during daytime, particularly for daily travel (Fig. 13 & Fig. 14) because people living in Khan Sen Sok travel long distance in the city almost every day during daytime. Rose (2010) found that 100% of urban people in Chennai Metropolitan experienced thermal discomfort during daytime and 75% were distressed due to the UHI intensity. Kotharkar et al. (2018) also found that the high temperature during daytime created human thermal discomfort. According to

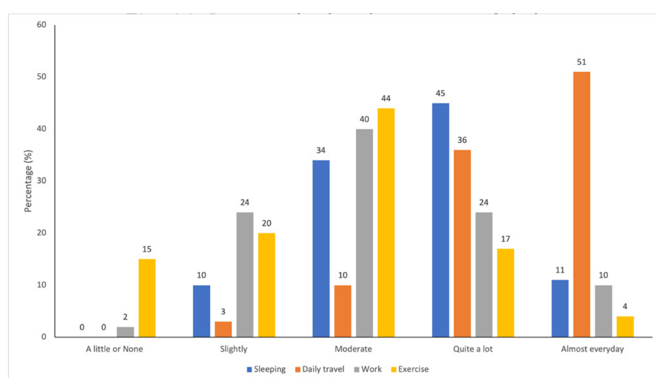


Fig. 14: Perceived urban heat stress of daily activities among surveyed respondents in percentage (%) in Khan Sen Sok.

Heaviside et al. (2017), the UHI intensity during daytime affected human health, especially thermal discomfort. The study of Zander et al. (2018) also found that people living in urbanized areas with high population density in the Philippines are more likely to experience urban heat stress. According to Arifwidodo & Chandrasiri (2020), urban heat stress poses health problems in the urban area and the effects of urban heat stress increased due to the increased temperature in Bangkok. Hence, the increased UHI intensity is responsible for human health, particularly human thermal discomfort and urban heat stress.

3. Conclusion and Policy Implication

In this study, we investigated the daily variation of urban heat island (DVUHI) and seasonal variation of urban heat island (SVUHI) intensities, as well as the characteristics of wind speed and direction, and the relationships between the UHI, wind speed, and human thermal comfort. We found that the average air temperature in Khan Boeung Keng Kang was higher than that in Khan Pou Senchey. The average air temperature difference was also higher in Khan Boeung Keng Kang than in Khan Pou Senchey. The DVUHI intensity was stronger during the daytime than nighttime and also stronger in the dry season than in the wet season. The hourly variation of the UHI intensity of selected days in dry and wet seasons had different characteristics during the daytime and nighttime. Hourly UHI intensity occurred during the daytime, and a cold effect occurred at night. Additionally, the SVUHI intensity was stronger in the dry season and during the daytime and weaker in the wet and night seasons. The UHI intensity is reduced by ventilation. Wind speed and direction are important in mitigating UHI intensity at the city scale. The study found higher wind speeds in Khan Pou Senchey could mitigate UHI intensity more than in Khan Boeung Keng Kang. The impacts of wind on UHI intensity depend mainly on wind speed and direction. Southwesterly winds during the wet season can mitigate the UHI effect. Additionally, UHI effects significantly correlate with wind speed during the day and night in both the wet and dry seasons. When wind speed is higher, UHI intensity is weaker. Hence, wind speed is important in mitigating the UHI intensity in the study area.

In short, this study demonstrated that the UHI intensity is higher in urbanized areas (Khan Boeung Keng Kang) than in suburban areas (Khan Pou Senchey) because high-rise buildings in Khan Boeung Keng Kang may inhibit incoming wind, which can mitigate the UHI intensity. Therefore, daily and seasonal UHI intensities are higher during the day than at night. This is the first study of the impacts of urbanization on the UHI effects in a case study of Phnom Penh city using ground meteorological data. This provides a preliminary result to demonstrate the variations of DVUHI and SVUHI and human thermal discomfort impacted by the UHI intensity. This result should be some implications for urban climate planning, such as building cubage and orientation, densification, etc., to increase ventilation and decrease the UHI intensity. This study expands understanding of the UHI effects that can help policymakers and/or urban planners create the appropriate UHI mitigation and adaptation measures. Furthermore, it is also the first result for further in-depth future research focusing on the relationship between the UHI intensity and thermal comfort for urban people in Phnom Penh city to enhance the urban quality of life.

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Declaration of competing interest

The authors have no competing interests to declare. All authors have read and approved the final, published version of the manuscript.

Credit authorship contribution statement

SE Bunleng: Equipment installation, research design, data collection and analysis, writing- original draft of article, reviewing and editing. CHOI Daniel M.: Equipment installation, data collection, reviewing and editing. CHHINH Nyda: Reviewing, commenting and editing. HAHNE Janalisa: Reviewing and commenting. YAV Net: Data analysis and map processing. KUPSKI Sebastian: Reviewing and commenting. RANG Chandary: Data analysis and figures producing. KATZSCHNER Lutz: Reviewing, commenting and editing. All authors have read and agreed to the published version of the manuscript.

Data availability statement

Raw data were collected by professional WCDMA/GSM weather stations installed in Khan Boeung Keng Kang and Khan Pou Senchey in 2021.

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Author's biography

SE Bunleng is currently the Lecturer, Researcher, Leader of the Climate Change and Water Group (CCWG), and Coordinator of Master of Arts in Geography, Department of Geography and Land Management, Royal University of Phnom Penh since 2012 until the present. He is responsible for teaching some courses including Geomorphology, Climate Change, and Soil Science. Bunleng is a PhD candidate in the Khmer Studies Program in the Faculty of Social Science and Humanities, Royal University of Phnom Penh, majoring in Hydroclimatology. His primary research interests relate to hydrometeorology, hydroclimatology, climate change, and geosciences. He published some papers, including 1) Preliminary reconstruction of Late Quaternary environment at Bat Trang, Southwest Cambodia; 2) Spatial growth of Phnom Penh, Cambodia (1973-2015): Patterns, rates, and socio-ecological consequences; and 3) Urban climate recommendations for urban planning in Phnom Penh, Cambodia. Bunleng is researching the Implications of Urban Heat Island Dynamics under Urbanization and Climate Change on Precipitation Patterns and Its Impacts on Socio-economic Development in Phnom Penh, Cambodia.

CHOI Daniel M. has been working as a visiting lecturer at the Department of Geography and Land Management, Royal University of Phnom Penh, since 2010. He is currently an advisor of the Climate Change and Water Group at the aforementioned department. His current research interests are hydrometeorology, climate change and FDM (Fused Deposition Modelling) 3D printing. He received his DPhil in Geography from Mansfield College, University of Oxford, UK.

CHHINH Nyda is currently the lecturer and researcher at the Department of Economic Development (DED) in the Faculty of Development Studies, Royal University of Phnom Penh (RUPP). He is responsible for teaching Introduction to Statistics, Quantitative Research Methods, Applied Research for DED, Geographical Information Systems and Remote Sensing. Nyda graduated from Flinders University, Australia, majoring in Environmental Risk Management. His research interests include disaster risk management/reduction, climate change adaptation and rural development. Previous research projects led by Chhinh were 1) Building Community for Disaster Resilience, funded by IDRC; 2) "Building Capacity to Adapt to Climate Change in Southeast Asia," funded by EEPSEA and International Development Research Center (IDRC), Canada, and 3) The Feasibility Study on "Payment of Forest Environmental Services in Cambodia" collaborated with Hue University in Vietnam, funded by SUMERNET. Some earlier research projects included 4) 'Costs and Benefits Analysis of Small-Scale Jatropha Curcas Plantation in Cambodia' funded by the Economy and Environment Program for Southeast Asia (EEPSEA), and 4) "Impacts of ENSO on Rice Production in Cambodia" funded by FAO Italy. Currently, Nyda is conducting research projects, including 1) Emergency Response Capacity Assessment at a local level using a tool known as Response Capacity Index (RC), 2) Impact Stories from a Development Project focusing on Smart Agriculture and 3) Mapping scholarship program for Southeast Asia for Cambodia.

HAHNE Janalisa is a research associate at the Institute of Climate and Energy Concepts in the field of urban climate, regional planning and climate adaptation. She holds a PhD degree in ecological accounting and has an international academic and working background in urban, energy and environmental planning as well as economic geography. Her main research interests are in urban climate planning and sustainable neighborhoods.

KATZSCHNER Lutz is a retired Professor Dr. for meteorology and urban climate from the University of Kassel. Currently, he is working with the Institute of Climate and Energy Concepts in the field of urban climate and planning. He is chairman of the working group guidelines for urban climate and planning and cities and climate change within the Association of German Engineers. He has many years in international experience and teaching and research in Europe, Latin America and Asia.

KUPSKI Sebastian is managing director at the Institute of Climate and Energy Concepts in the field of urban climate, regional planning and climate adaptation. His specialty is an urban climate in all mentioned planning scales. His research aim is to develop adaptation tools for cities based on urban climate maps. He is chairman of the working group guidelines for communication and visualization.

YAV net is a contract lecturer in the Department of Geography and Land Management, Royal University of Phnom Penh, since 2016 until present. He is currently responsible for lecturing Cartography, Geographic Information System (GIS) and Remote Sensing (RS) courses for graduate and undergraduate students. Further, he has also expertise in Environmental Impact Assessment (EIA).

RANG Chandary is a contract lecturer in the Department of Geography and Land Management, Royal University of Phnom Penh, from 2018 until the present. He is currently responsible for lecturing Cartography and Geographic Information System (GIS) courses. He conducted many research projects and program evaluations on public health and vector-borne diseases. In addition, he is expertise in data management, analysis, and data visualization.

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