Urban heat island analysis for Bangkok: multi-scale temporal variation, associated factors, directional dependence, and cool island condition

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ABSTRACT: This study analyzed urban heat island characteristics in Bangkok, observed during a period of 10 years (2006–2015) with emphasis on the dry season when the urban heat island is intensified in both daytime and nighttime as compared to the wet season. December-January was found to be the months of peak urban heat island intensity (UHII) in terms of average. The intensity is relatively large at night due to the faster cooling rate during the early evening at the rural site whose thermal admittance of land surface is lower than the urban site. UHII is slightly larger during the weekdays than the weekend, suggesting certain degree of influence of anthropogenic heat emitted in the urban area. UHII is negatively correlated with most of rain, cloud, relative humidity, and wind speed variables. The assessment of polar plots shows UHII dependence on wind direction. The statistical regression models relating UHII to selected meteorological variables are capable of explaining the variability of the original data by 82% for daytime UHII and 66% for nighttime. Southwesterly wind direction and persistence were found to be important in modulating UHII, and both appear in the final regression models. The presence of dry-season cool island events was also investigated, and it was found that they are generally induced by the high intensity of urban-alone/urban-rural rain, cloud, relative humidity, or urban wind speed (or combined). Overall, the findings from the study provide enhanced perspectives, which can support urban policy and planning related to weather for the study area.

KEYWORDS: urbanization, temperature, urban climate, cool island, Thailand

INTRODUCTION

Urbanization involves land cover modification with expanded built areas (i.e., urban sprawl), increased population accompanied by human activities, and more energy consumption. In a highly urbanized area or city, the presence of developed areas, tall buildings, and dense roadways with surface concrete/asphalt paving often come with reduced green areas, setting a topographical contrast between the urban area and its nearby rural area. Anthropogenic heat emissions due mostly to energy usage (fuel combustion and electricity) may be relatively large in urban areas [1,2]. These factors can induce changes in climatic conditions between the urban and rural areas. Urban heat island (UHI) has been known as a phenomenon where urban temperature is higher than rural temperature [1,3]. The UHI intensity (UHII) is defined as the difference between urban air temperature ($T_u$) and rural air temperature ($T_r$) i.e., $\Delta T_{u-r} = T_u - T_r$. Air temperature is generally referenced at a near-surface level within an urban canopy. Nevertheless, land surface temperature and air temperature aloft can also be used to define UHII [3–5]. In other words, the UHI definition considered here is for urban canopy layer, which generally represents microscale conditions influenced by buildings, vegetation, and intervening spaces [3]. Since near-surface air temperature is simply utilized in the UHI calculation, data recorded...
Urban temperature tends to be higher than rural temperature because of the physical properties of urban surface, especially lower albedo and larger thermal admittance [6]. Thus, the urban surface tends to absorb more solar radiation and store more heat during the daytime and release the stored heat back to the atmosphere in the nighttime while the rural surface warms and cools relatively faster. These cause UHI to be most intensified at night. During calm wind conditions, a shallow convective layer may develop above an urban core and then cause air to flow from its outer areas towards and converge at the urban core, which lessens the ventilation of air pollutants. Moreover, UHI is known to intensify during an extended hot period or a heat wave, making urban population in large cities more vulnerable to heat or thermal pollution [7].

Temperature, health problems, and mortality have been found to be associated in urban studies [8]. From a macroscopic viewpoint, UHI correlates with population size and urbanization extent [9,10]. In the summer, relatively warm temperature leads to a higher power demand for air conditioning and thus larger heat emitted to the atmosphere. Therefore, the issue of UHI has direct implications for urban sustainability in environment, energy, and health policy and planning. In fact, UHI is a central subject in the field of urban climates, which has been widely studied [11–13].

Bangkok is the capital city of Thailand (Fig. 1) and the largest province in terms of population and urbanization. It is a strategic, economic hub that accounts for as much as 46% of the total GDP (as of the year 2015), according to the Office of the National Economic and Social Development Board. In fact, its continuous growth is not limited to Bangkok but extends to its neighboring areas [14], combined as a large urban agglomeration called the Greater Bangkok (GBK) (Fig. 1b). Administratively, GBK consists of six provinces: Bangkok, Samut Prakan, Samut Sakhon, Nonthaburi, Nakhon Pathom, and Pathum Thani. Given the significance of Bangkok, its climatic conditions are inevitably an important issue for the public. A number of UHI-related studies have been conducted for the province but varied greatly in type of UHI, objec-
tive, method, and analytical intensiveness. As a pioneered UHI investigation, Boonjawat et al. [15] employed air temperature data measured in 1998 from a private network of automated stations to assess UHI in Bangkok and supplemented discussion using some landscape and satellite images. Jongtananom et al. [16] reported preliminary results on the average diurnal and monthly variations of UHII in three selected major provinces (including Bangkok). Paksarnseree et al. [17] related seasonal change in air temperature in terms of cooling rate for various subdivisions over the city to their physical landscape properties (street/park/water/building spaces and building-floor area) in four separate years starting from 2000. Satellite-based land surface temperature data can be utilized to determine the extent of urban expansion and surface urban heat island (SUHI), potentially useful for city planning and developing UHI mitigation strategies. Such satellite-based data were applied to Bangkok by some studies [5, 18]. To our knowledge, no studies have yet been found for comprehensive characterization of UHI and its meteorological association for Bangkok, and none has addressed cool island conditions in the province. The cool island is the phenomenon opposite of UHI i.e., rural temperature being larger than urban temperature (i.e., negative UHII). In the literature, the cool island has not been much addressed or often briefly mentioned [19, 20]. Thus, it is of current interest to examine the cool island in more details. Many of the above-mentioned UHI studies for Bangkok employed observational data with a limited period and did not provide attention to the selection of reference urban and rural sites, which may result in less reliability in their reported findings. For UHI studies, it is crucial to properly select the reference urban and rural sites [18, 21]. Our effort here aims to fill such gaps and, importantly, improve the existing understanding of UHI for Bangkok, which can be useful information to support environmental policy and planning towards the goal of urban sustainability in the future.

MATERIALS AND METHODS

Study area

Bangkok (13°45′ lat. and 100°28′ lon.) is geographically situated in the central plain of Thailand, which is the alluvial basin of the Chao Phraya River. It is adjacent to the Gulf of Thailand to the south, with a distance of 25 km from the city center and the coast. The terrain elevation is generally flat and on average 1.5 m msl (above mean sea level). Bangkok is administratively divided into 50 districts and covers a total area of 1568.7 km². According to the National Statistical Office of Thailand, it has a total registered population of 5.5 million and a large latent (non-registered) population which is estimated to be about 40% more. As mentioned previously, the Greater Bangkok (GBK) agglomer-
ation comprises Bangkok and its five surrounding provinces with a total area of 7762 km² and a population of over 10 million. In the southern part of GBK (especially, Samut Prakan and Samut Sakon), many industrial factories are present. The general climate of GBK is like most part of Upper Thailand, which is influenced by the northeast and southwest monsoons [22,23]. The former monsoon prevails during Nov–Feb and brings cool dry air masses from mainland China, corresponding to the winter. In Mar–Apr, the northeast monsoon becomes weakened, and air temperature begins to increase, resulting in the warmest period of the year (i.e., the summer). Given no strong influences from the two monsoons during these two months, southerly winds from the Gulf of Thailand synoptically prevail. The southwest monsoon approximately starts in May and lasts until October, bringing abundant moisture from Indian Ocean and the Gulf of Thailand along its passage and thus substantial rain. According to these distinct seasonal features (Fig. 2a), the dry season (Nov–Apr) and the wet season (May–Oct) were considered in our UHI assessment. The wet season contributes over 80% of total annual rainfall, based on the obtained rainfall data. Because the dry season crosses over two calendar years, the dry season of a particular year is formed by Nov–Dec of the previous year and Jan–Apr of that year.

Data
Several weather stations of the Thai Meteorological Department (TMD) located in the GBK were initially considered. However, their monitoring differs in temporal coverage (e.g., 8–35 years), hour-of-day span (e.g., daytime only as opposed to both daytime and nighttime), and sampling frequency (e.g., hourly, three-hourly, and daily), thus posing difficulty in choosing a pair of reference urban and rural sites. Initially, three-hourly data (including temperature, rain, cloud cover, relative humidity, and wind speed/direction) from eight stations were obtained and also checked for time coverage, implausible values and data adequacy for every variable (here, temperature, rain, cloud cover, relative humidity, and wind). The amount of non-missing (i.e., valid) values was found to be at least 85%. Given the long-term data used in the study, we performed additional data checking as follows: (a) valid values within the ranges of 0–50 °C for temperature and 0–100% for relative humidity, and (b) non-outliers to be within the range of mean ± 5 times standard deviation. It is noted that temperature and humidity were measured at 1.5 m agl (above ground level), and wind measurement is at 10 m agl.

In selecting the reference sites for the analysis, they should in principle not be close to a large water body or river. In the study, we conducted a field visit to each weather station (six in total) located within the study area to examine its actual environment. We computed total built-up amount corresponding to each station using a 10-km radius using a land cover database of the Land Development Department (LDD) for the year 2009 (Fig. 1). It is noted that no size or radius has been universally proposed for use to classify the type of station in urban heat island studies. For example, Yang et al [24] tried a set of radii (ranging 1–20 km) and chose 7 km as the threshold. According to the above procedure, we found S1 and S2 (separated by 8 km) in Bangkok as the urban sites and S3 in Nakhon Pathom as the rural site representatively. Both S1 and S2 share a similar background, which is a business area with buildings, houses, parks, and streets. Their total built-up areas are about 80% (Fig. 1d and e). Fish-eye photographs were also taken during the station visits using an all-sky camera set at a height of 1 m agl to estimate sky-view factor (SVF), defined as the ratio of the area of sky portion to that of the hemisphere. The SVF values at both S1 and S2 are >60% (here, 63% and 80%, respectively) (Fig. 1d and e), indicating no severe obstruction or blocking of air ventilation and radiation. Because the data at both stations tend to be well correlated (e.g., >0.9 for three-hourly temperature and relative humidity), average values from the two stations were then used, and the middle location between both stations was designated as the official reference urban site (S_u). Station S3 is the reference rural site (S_r). Its background is an open green area with a total built-up area of 22% and a SVF of 82% (Fig. 1f). The distance between S_u and S_r is about 70 km. We further roughly estimated total built-up amount based on an alternative dataset (Google-Earth satellite images) but at a closer proximity (2-km radius) for the year 2010 and found 93% at S1, 85% at S2, and 25% at S3 as a result (not shown), which is also consistent with those based on the LDD data. Arguably, the fair amount of total built-up area at S3 may theoretically not classify it as an ideal rural site. In the current context, it is nonetheless used as our best rural-site candidate. In view of local climate zone classification [6], given the available information, S_u appears to match local climate zone (LCZ) Type 2 (compact midrise) while S_r approximately matches LCZ Type 9 (sparsely built).
The temporal coverage of the three-hourly data at Su and Sr is from 2006–2015 (10 years). The amount of non-missing (i.e., valid) values was found to be at least 85% for every variable (here, temperature, rain, cloud cover, relative humidity, and wind) at each station. Given the three-hourly data, 10–19 LT (local time) were used as the daytime hours while the nighttime hours consisted of 22 LT (of current day) and 01–07 LT (of the next day). In addition to the three-hourly data, long-term (35 years, 1981–2015) daily maximum and minimum temperature data were obtained and averaged as daily mean temperature. Both stations commonly have a significantly positive trend of temperature (0.41 °C/decade at Su and 0.24 °C/decade at Sr, Fig. 2b), which is attributed to the combined result of urbanization and climate change (i.e., global warming). Previous studies [22, 25] reported the warming trends of temperature across Thailand over recent decades as a result of climate change. Given that both sites are located in GBK, the larger trend found at Su is thus due to the effect of relatively high urbanization.

RESULTS AND DISCUSSION

Monthly and diurnal variation and weekday-weekend difference

The monthly variation (or annual cycle) of UHII shows seasonality for both daytime and nighttime UHII (Fig. 2c), which is larger (smaller) in the dry (wet) season in terms of mean UHII. The urban heat island is most intensified during Dec–Jan. The maximum UHII based on the three-hourly data is as much as about 10 °C in Apr. According to this, dry-season is the main emphasis of this study. It is noted that the wet season has more precipitation, causing complexity given that soil and surface moisture is well present and can be persistent due to its long memory [31] and then impacting climatic conditions, including temperature, through land-surface processes. The UHI analysis for the wet season may not be as straightforward and requires a careful treatment, which is beyond the current scope of this study. Nighttime UHII is generally stronger than the daytime counterpart as reported in [10, 16, 19, 27, 28]. The cool island (i.e., negative urban heat island) is also present every month. UHII varies with hour of day, as seen in Fig. 3a for the dry season. The intensity is relatively high, starting from 22 LT till 7 LT. Mean UHII in Singapore City peaks at 21 LT (i.e., a couple of hours after sunset) [19]. In general, both urban and rural surfaces become warm after sunrise and peak in the mid-late afternoon (Fig. 3b). As seen, the rural surface (or air) typically gets warm faster during the day and cools faster in the evening. To explain this, surface-air heating rate at each of the urban and rural sites is examined (Fig. 3c), which is defined as follows:

\[
\left(\frac{\Delta T}{\Delta t}\right)_n = \frac{T_n - T_{n-3}}{t_n - t_{n-3}},
\]
where the left-hand side term is the heating rate at current hour \( t_n \), \( T_n \) is the temperature at \( t_n \), and \( T_{n-3} \) is the temperature at three hours earlier (given the three-hourly data). At both sites, the warming rate (temperature at 10 LT minus that at 7 LT) peaks at 10 LT (5.8 °C/3 h) while the maximal cooling rate (−4.5 °C/3 h) is at 19 LT, but with the larger magnitudes at the rural site. This can be explained by the concept of thermal admittance. From the previous sub-section (Data), the urban and rural sites are approximated to LCZ types 2 and 9, respectively, which have the corresponding values of thermal admittance of 1200–2200 and 1000–1800 \( \text{Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1} \), respectively (as the suggested values given in Stewart and Oke [6]). Thermal admittance is a property of a surface or material to absorb/release and store heat. The smaller values at the rural site correspond to shorter time (i.e., faster) of the rural surface to respond to and store absorbed solar radiation as heat, which is due mainly to the presence of more open areas with less buildings. Comparing with the Singapore City study using hourly data [19], the maximal cooling rate at most of the urban and rural sites was found at 18 LT.

Whether the urban heat island is dependent on anthropogenic (human-generated) heat is of additional interest because urban areas typically consume considerable energy, which eventually dissipates into heat. Anthropogenic heat sources in an urban area include transportation, cooling and heating buildings, manufacturing and lighting [1, 2, 29]. In context of surface energy balance, such heat may add to sensitive heat, raising surface air temperature. Here, UHII and temperature over the weekday (i.e., working days) and weekend periods are compared. Mon–Fri were assigned as weekdays, and Sat–Sun were assigned as weekend. It is expected that energy usage or heat emission becomes larger during the weekdays at both urban and rural sites, causing weekday temperature to be higher than the weekend for all cases (Fig. 4b). However, for urban heat island, only nighttime UHII shows a contrast of 0.1 °C (significant at a 0.1 level) between the two periods (Fig. 4a). This is attributed partly to that, in the nighttime, the urban weekend has a more apparent decrease in human activities than the rural weekend. Thus, it is possible to state that both UHII and temperature are dependent on anthropogenic heat but to a small degree whereas land cover is the major factor influencing UHII for the study area. It is noted that the non-parametric Wilcoxon rank sum test was employed to test the statistical significance of difference in the means of two samples.

**Meteorological factors and directional dependence**

UHII is known to be influenced by other meteorological variables e.g., rain (R), cloud cover (CC), and relative humidity (RH). The first two variables are known to be associated with the surface energy balance, in which they modulate solar radiation and partitioning heat from the surface to the atmosphere into sensible heat and latent [30]. Relative humidity is a measure of available moisture in the air relative to the saturated condition, which is temperature-dependent following the Clausius-Clapeyron relationship by which relative humidity decreases with increased temperature. In general, relative humidity is also associated with rain and cloud in the same direction. Besides urban weather conditions at the urban site, it is possible to include the urban-rural difference of a meteorological variable since UHII may be influenced by rural weather conditions as well. Liu et al [31] found that urbanization tends to decrease humidity in the Beijing area, leading to urban-rural humidity contrast. For wind, large
Table 1 Correlation between dry-season daytime and nighttime UHII and meteorological variables and the MLR results.

(a) Correlation

<table>
<thead>
<tr>
<th>Variable</th>
<th>UHII&lt;sub&gt;day&lt;/sub&gt;</th>
<th>UHII&lt;sub&gt;night&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&lt;sub&gt;s&lt;/sub&gt; (mm/3 h)</td>
<td>-0.24 (N = 1748)</td>
<td>-0.32 (N = 1750)</td>
</tr>
<tr>
<td>ΔR&lt;sub&gt;u−r&lt;/sub&gt; (mm/3 h)</td>
<td>-0.28 (N = 1748)</td>
<td>-0.21 (N = 1750)</td>
</tr>
<tr>
<td>CC&lt;sub&gt;u&lt;/sub&gt; (deca, in tenth)</td>
<td>-0.22 (N = 1750)</td>
<td>-0.42 (N = 1750)</td>
</tr>
<tr>
<td>ΔCC&lt;sub&gt;u−r&lt;/sub&gt; (deca, in tenth)</td>
<td>-0.14 (N = 1750)</td>
<td>0.16 (N = 1750)</td>
</tr>
<tr>
<td>RH&lt;sub&gt;u&lt;/sub&gt; (%)</td>
<td>-0.66 (N = 1750)</td>
<td>-0.46 (N = 1750)</td>
</tr>
<tr>
<td>ΔRH&lt;sub&gt;u−r&lt;/sub&gt; (%)</td>
<td>-0.87 (N = 1750)</td>
<td>-0.65 (N = 1750)</td>
</tr>
<tr>
<td>WS&lt;sub&gt;u&lt;/sub&gt; (m/s)</td>
<td>0.00 (N = 1742)</td>
<td>-0.09 (N = 1419)</td>
</tr>
</tbody>
</table>

(b) MLR

UHII<sub>day</sub> (°C) = 0.384 − 0.024 ΔR<sub>u−r</sub> − 0.108 ΔRH<sub>u−r</sub> − 0.225 WD<sub>u</sub>(SW) + 0.366 PER

Coefficient (standard error, p-value):
- Intercept (0.039, < 0.01), ΔR<sub>u−r</sub> (0.003, < 0.01), ΔRH<sub>u−r</sub> (0.003, < 0.01), WD<sub>u</sub>(SW) (0.042, < 0.01), PER (0.013, < 0.01)

UHII<sub>night</sub> (°C) = 1.234 − 0.101 ΔRH<sub>u−r</sub> − 0.109 CC<sub>u</sub> − 0.120 WS<sub>u</sub> + 0.323 WD<sub>u</sub>(SW) + 0.353 PER

Coefficient (standard error, p-value):
- Intercept (0.085, < 0.01), ΔRH<sub>u−r</sub> (0.003, < 0.01), CC<sub>u</sub> (0.009, < 0.01), WS<sub>u</sub> (0.041, < 0.01), WD<sub>u</sub>(SW) (0.060, < 0.01), PER (0.019, < 0.01)

N is the number of pairs or records used in calculation. All correlation results are statistically significant at a 0.05 level. WD<sub>u</sub>(·) is the vector-average urban wind direction whose value is 0 and 1. WD<sub>u</sub>(SW) corresponds to the southwesterly wind, represented by the third quadrant as seen in the polar plots (Fig. 5a). PER (°C) is the persistence of UHI condition.

Fig. 5 Polar plots of UHII and wind rose diagrams based on urban wind of the dry season in 2006–2015.

wind speed (WS) can advect heat out of a city and enhance vertical heat mixing, reducing UHII [27]. But wind inside the city can be considerably slowed down by relatively large surface roughness due to the presence of tall or sizable built structures, which is the case of the urbanized areas in Bangkok [32]. Thus, urban wind is essentially an important variable.

Here, correlation analysis was performed to examine the general association of UHII in the dry season and rain (R), cloud cover (CC), and relative humidity (RH) at the urban site as well as their urban-rural differences, and urban wind speed (Table 1), denoted by R<sub>u</sub>, ΔR<sub>u−r</sub>, CC<sub>u</sub>, ΔCC<sub>u−r</sub>, RH<sub>u</sub>, ΔRH<sub>u−r</sub>, and WS<sub>u</sub>. It was found that UHII (both daytime and nighttime) are significantly negatively correlated with all variables for most of the cases (12 out of 14). For R<sub>u</sub> and ΔR<sub>u−r</sub>, correlation ranges from −0.32 to −0.21. Rain brings more moisture to the surface, and then the surface gives out more latent heat and less sensible heat to the air, then reducing temperature. For CC<sub>u</sub>, correlation is negative (−0.22) for daytime. During the day, clouds reflect shortwave radiation back into atmosphere, causing less solar radiation at the surface to be available to sensible heat. On the other hand, during the night, longwave radiation emitted from the surface can be trapped by clouds and radiated back downward to surface, warming the surface air. Instead, negative
correlation is seen for nighttime (−0.42), which is
perhaps caused by the net effect of both urban and
rural clouds. However, correlation with ΔCCu−r
becomes in line with the above physical explana-
tion i.e., negative (−0.14) for daytime and positive
(0.16) for nighttime. Correlation with both RHu and
ΔRHu−r is negatively strong (>0.5), which may be
explained by the combined effect of the Clausius-
Clapeuron relationship and the association among
humidity, cloud, and rain (i.e., more humidity tends
to give more clouds/rain, and vice versa). By check-
ing correlation for any pair of Ru, CCu, and RHu, it
is positive, ranging from 0.2–0.6 (not shown). For
WSu, no correlation with UHII is observed in the
daytime; nighttime correlation is negatively small
(−0.09) but still significant. It is noted that WSu was
computed as the speed of the vector-average wind
over all daytime/nighttime hours.

The directional dependence of UHII for the dry
season in both daytime and nighttime was inves-
tigated using polar plots [33] (Fig. 5). The cor-
corresponding wind rose diagrams are also given. It
is noted that a polar plot displays a quantity of
interest (here, UHII) as a function of wind speed
and direction while a wind rose diagram displays
the frequency of wind occurrence by wind sector
and speed interval. Both polar plots and wind
rose diagram use the standard definition of wind
direction i.e., wind blowing towards the center and
the angle is clockwise from the north axis. The wind
rose diagrams for daytime and nighttime are sim-
ilar, showing two prevailing winds (northeasterly-
and southerly-southwesterly). The former is
due mainly to the northeast monsoon, but the latter
is the combination of sea breeze and the sum-
er Gulf wind. Sea breeze is generally well present
along the coastal areas next to Eastern and Central
Thailand in the middle of the dry season [32, 34].
The regional Gulf wind (local name: Tapao wind)
blows from the middle Gulf of Thailand northward
during the late dry season. Daytime UHII is rela-
tively strong in the first quadrant (i.e., northeaster-
ly) but relatively weak in the third (southwester-
ly). The weaker intensity in the third quadrant
may be partly attributed to cool southerly wind
from the Gulf or to warm air from the city core
traveling northward to the rural area by southerly
wind. The former lowers urban temperature while
the latter raises rural temperature, each of which
decreases UHII. These hypotheses are nonetheless
subject to further investigation, which is not in the
scope of this study. Nighttime UHII tends to be
strong and more uniform throughout all direction
in comparison with its daytime counterpart with the
third (southwesterly) and fourth quadrants (north-
weste rly) being the most intense.

Statistical relationship
It is generally useful to formulate a statistical rela-
tionship of UHII and its associated factors, which
can help to identify a set of variables influencing
the urban heat land. Multiple linear regression
(MLR) has been applied in urban heat island stud-
ies [28, 35]. It was adopted here due to its simplic-
ty and acceptable explanatory power for total variance
(as shown later). In this study, the seven daily me-
teorological variables discussed earlier (Table 1a)
were considered. Moreover, day-to-day UHII per-
sistence (PER) was included to represent the possi-
ble influence of the past condition on the present
condition (i.e., providing the background state),
which can then increase the UHIIi predictability of
the MLR. UHII persistence is set as the value of
UHII on the previous day, which was found to be
well correlated with UHII of the present day (0.8
for daytime and 0.7 for nighttime). Urban wind
direction (WD) (used in the polar plots) was also
included as a factor variable (whose value is 0 or
1). Here, the four major wind sectors or quadrants
were considered, which are NE (northeasterly),
SE (southeasterly), SW (southwesterly), and NW
(northwesterly). Hence, a total of nine were used
as the initial input or explanatory variables for the
MLR below:

\[
UHII = \sum_{i=1}^{n} a_i X_i + b,
\]

where \( a_i \) and \( b \) are the coefficient of the explanatory
variable \( X_i \) and the intercept, respectively. In the
MLR modeling, certain initial variables with strong
correlation with others were excluded to avoid co-
linearity problem. Backward stepwise elimination
was applied to variable selection to reach a parsimo-
nious set of the final variables in the regression. The
adequacy of each regression model was also checked
using diagnostic plots (for linearity, normality, con-
stant error, and influential outliers), and found to
be acceptable. The total variance in the original
daytime UHII data was captured by as high as 82%
while that of nighttime UHII is explained by 66%
(Table 1b). Most of the meteorological variables in
the final models have a negative coefficient, consis-
tent with the correlation results in Table 1a. As for
wind direction, onlysouthwesterly wind is finally
maintained. Its coefficient is negative (−0.23 °C−1)
for the daytime model but positive (0.32 °C⁻¹) in the nighttime model, which is in agreement with the polar plot results where UHII appears to be suppressed and amplified in the third quadrant, respectively. Persistence is also shown to be another important variable in the regression models.

**Cool island condition**

It has been shown previously (Fig. 2c and Fig. 3a) that the cool island (UHII < 0 °C) occurs in Bangkok. Here, the cool island in the dry season was investigated, complementary to the dry-season urban heat island discussed so far. Two conditions of the cool island were considered: all-inclusive (UHII < 0 °C) and intense (−1 °C). It was found that about 19% and 9% of the total three-hourly records are registered as the two cases, respectively (Fig. 6a). The majority of occurrences (> 90%) were found during the day (10–19 LT, with the peak frequency seen at 16 LT) for both cases (Fig. 6b). The shape of cool island intensity distribution at each hour (Fig. 6c) tends to be skewed (i.e., long-tailed) unlike that of UHII (Fig. 3a) which appears to be less skewed or more of a normal distribution. In the afternoon (13–16 LT), the cool island is more apparent, with its mean and maximal intensity being greater than 1 °C and 8 °C (in magnitude), respectively. What causes or influences such daytime cool island? To answer this, the seven variables listed in Table 1a were re-visited. Our hypothesis is that the cool island in fact does not occur as normally expected events, and the shift to negative UHII is more induced by the intense shift of urban-rural contrast (as opposed to urban-alone variables). Accordingly, the average values of $R_u$, $\Delta R_{u-r}$, $CC_u$, $\Delta CC_{u-r}$, $RH_u$, $\Delta RH_{u-r}$, and $WS_u$ were assessed for the following three UHII cases (positive or $\geq 0$, negative or $< 0$, and negatively large or $< -1$) (Fig. 7). It is apparent that all of the urban and urban-rural variables change in the same direction (from low to high values) with UHII case, which is in agreement with the correlation results. Thus, it is possible to state that the cool island is induced by the increased intensity of one or more of these variables.

**CONCLUSION**

The key findings from the current study are as follows:

(a) The urban heat island is intensified in the dry season, especially in Dec–Jan. UHII is relatively large at night due to the faster cooling rate during the early evening at the rural site where surface thermal admittance is lower than at the urban site.

(b) UHII is slightly larger during the weekdays than the weekend, suggesting certain influence of anthropogenic heat and land cover as the major factor influencing UHII. Thus, attention should be paid to land cover in the mitigation of urban heat island.

(c) UHII is negatively correlated with urban rain, urban-rural rain, and urban wind speed. At daytime, negative correlation with both urban cloud and urban-rural cloud is potentially caused by more shortwave radiation reflected by clouds. At night, positive correlation with urban-rural cloud was observed due possibly
Fig. 7 Differences in urban-rural cloud cover, rain, and relative humidity by UHII case. The results are based on the three-hourly data over 10–19 LT, dry season in 2006–2015.

to longwave radiation trapped by clouds and radiated back downward. Both urban relative humidity and urban-rural relative humidity are negatively correlated with UHII.

(d) The regression models of daytime and nighttime UHII acceptably explain the variability of the original data and thus have the potential utilization in the daily forecasting of weather-related energy or electricity demand.

(e) The cool island phenomenon is generally induced by certain favorable urban-rural contrast in rain, cloud cover, and relative humidity.

Other aspects related to the urban heat island in Bangkok are encouraged for future studies e.g., application of numerical modeling, synoptic atmospheric pattern, and land cover change with spatial assessment. Air pollutants (especially, particulate matter) can also influence the urban heat island because they affect solar radiation and visibility [36], then modulate air temperature. Lastly, given that Thailand has also experienced extremely high temperatures [37], the development of urban heat island under such hot conditions is of additional interest.

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REFERENCES

5. Srivanit M, Hokao K, Phonekeo V (2012) Assessing the impact of urbanization on urban thermal envi-


